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POLARIZATION UTILIZATION IN RADAR TARGET
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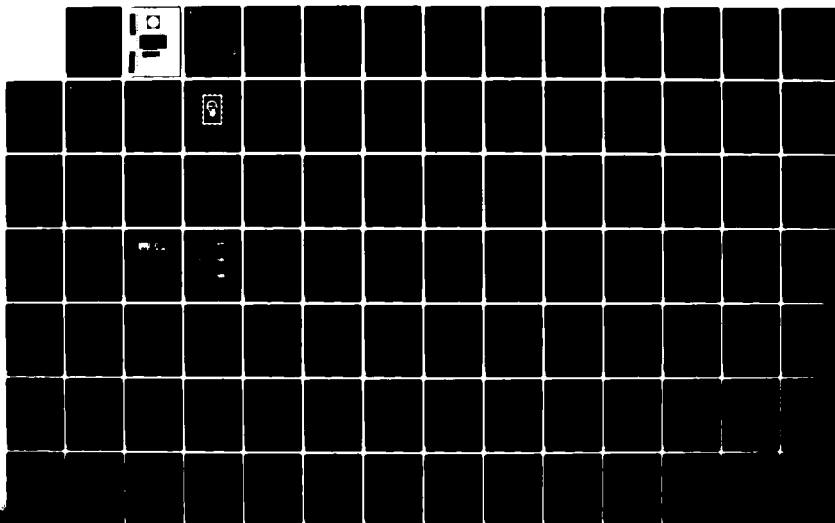
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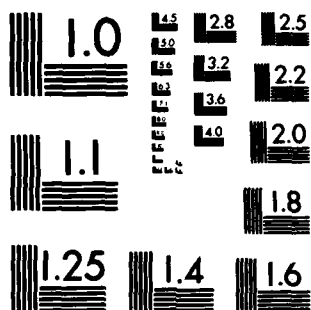
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W M BOERNER ET AL. 14 DEC 83

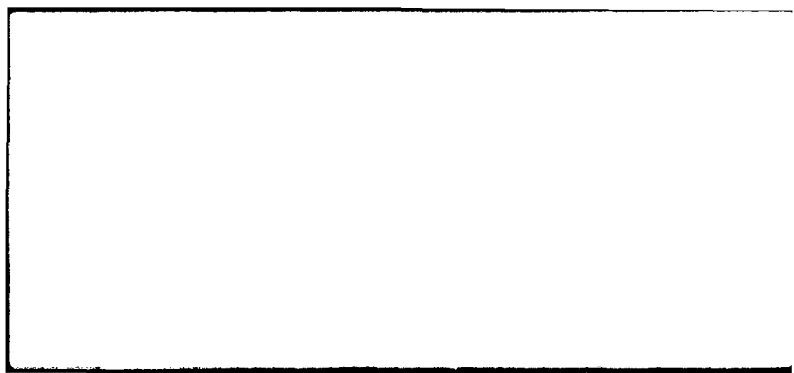
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(2)

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POLARIZATION UTILIZATION IN RADAR TARGET RECONSTRUCTION: C-Wide (Multi-Frequency) Band Relationship of a Target's Characteristic Operators with Its Unique Set of Natural Eigenfrequencies

W-M. Boerner, J.R. Huynen, N.C. Mathur, et al.

FINAL REPORT

UIC-EECS-CL-EMID-ARO/EL.83-12-14
Contract No. US Army DAAG-29-80-12-0027

1983 December 14

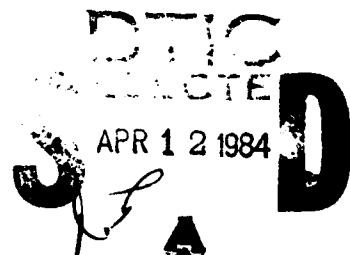
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REPORT IDENTIFICATION PAGE

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Radar polarimetry, polarization scattering matrix, Poincare' polarization sphere, Kennaugh's target characteristic operator (polarization fork), Kennaugh's target ramp response identity, Huynen's Mueller matrix target parameters, Kennaugh's K- Pulse & target eigenresonance theory, polarimetric target downrange & crossrange imagery; model-free polarimetric clutter description, Aitoff, Mollweide & Lambert		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) projections of the poi sphere. OVERALL ACHIEVEMENTS: During the tenure of this initiation contract on Polar- ization Utilization In Radar Target Identification a center of excellence for re- search in high resolution radar polarimetry was established within the Electro- magnetic Imaging Division (EMID), Communications Laboratory (CL), Department of Electrical Engineering and Computer Science (EECS), University of Illinois at Chicago (UIC) with the express purpose of advancing theoretical, computational Continued . . .		

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20. Abstract (Continued)

and experimental methods for radar target detection in clutter; separation of useful target vector signal from noise and clutter; classification of targets and/or clutter; target and/or clutter imaging, as well as target identification. To assist us in this endeavor, the College of Engineering, UIC, initially made available 2,200 sq.ft. laboratory space which now has expanded to 9,000 sq.ft. within SEL-4209/4210/4211 with adjacent side rooms, housing the CL-office, work and laboratory space for 18 research assistants and a DEC-VAX 11/750 and 780 Research Computer Processing System with some peripheral image processing, printing, color-graphics processors which were made available with partial funding from DoD-research offices and need to be further expanded, (Chapter VI). During the tenure of this contract ten M.Sc. Theses on topics related to polarimetric target imaging and geoelectromagnetic sounding were completed, and another five M.Sc. and three Ph.D. Theses will be scheduled for defense during this fiscal year 83/84 (Chapter III). On the average, some 18 papers and reports were published annually, four citations were awarded to the principal investigator who carried editorial duties for four separate international journal publications endeavors (Chapter IV), and he, together with some of his collaborators, presented two to three ONE or TWO-DAY short courses per quarter on the "Advancement of High Resolution Radar Polarimetry" to the National Radar Industry or Laboratories during the last two years (Chapter V).

SPECIFIC CONTRIBUTIONS: One of the prime objectives was to succinctly survey the American, European, Russian and Far-Eastern literature and to develop systematically a unified theory with notations and definitions according to IEEE standards on "High Resolution Radar Target Polarimetry" (see list of publications: Chapters I, II). This endeavor was crowned with partial success and the principal investigator was invited to write-up a series of four basic papers for the IEEE-AES Journal on the "History, Theory, Advancement, Applications and Future Trends in High Resolution Radar Polarimetry", the first of which will appear in early 1984. In our various analyses, we have considerably advanced basic understanding of Kennaugh's target characteristic operator (polarization fork) theory and Huynen's Mueller matrix decomposition theory; a model-free approach to polarimetric clutter description was introduced; and Kennaugh's target characteristic operator theory was generalized from the symmetrical (monostatic reciprocal) to the asymmetrical polarization scattering matrix case which prevails in the monostatic non-reciprocal and/or bistatic cases. The difficult problem of relating the broadband target characteristic operator theory with that of its unique set of natural eigenfrequencies, both posed by Kennaugh, has been analyzed in depth proving that hitherto used assumptions of single pole description is not correct for complicated shapes and that indeed the residues of the poles related to the natural eigenfrequencies are polarization dependent (Chapters I, II), requiring extensive further studies.

RECOMMENDATIONS: In Chapter II, the current state of the art is carefully reviewed, recommendations for additional, in parts extensive studies are made, and future trends in the "Advancement of High Resolution Radar Polarimetry" are assessed.



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ERRATA:

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Principal Investigator:

Wolfgang-M. Boerner / 1983 Dec 29.

Dr. Wolfgang-M. Boerner / Date
Professor, Electrical Engineering
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Corrections of ARO Final Report, Contract # US Army DAAG-29-80-12-0027, entitled Polarization Utilization in Radar Target Reconstruction: C-Wide (Multi-Frequency) Band Relationship of a Target's Characteristic Operators with Its Unique Set of Natural Eigenfrequencies, by W-M. Boerner, J.R. Huynen, N.C. Mathur, et al., 1983 December 14.

Page Chapter Line

vii 15 Appreciation is extended to Dr. Henry W. Mullaney
3 I.1 14 (seeker) radar deployment for the distinct
4 1.1.2 40 and equally important and must be used in simultaneity.
5 1.1.5 17 information using intra-pulse polarization state switching (IPPAR)
7 I.2 equation (1.2.1)

$$\begin{bmatrix} E_h^s \\ E_v^s \end{bmatrix} = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix} \quad \text{or } \underline{E}^s = [S] \underline{E}^i$$

9 Table 1 (T.3) $\underline{h}(t) = a_H \cos \omega t \hat{h}_H + a_V \cos (\omega t + \delta) \hat{h}_V$

9 Table 1 (T.6) $\cos \delta = \sin^2 \delta$

10 Table 1 (T.8) Modified Stokes Vector

where

$$g_0^2 + g_1^2 + g_2^2 + g_3^2 = I^2 + Q^2 + U^2 + V^2$$

$$\underline{g}_m = \{ 1/2(I+Q), 1/2(I-Q), U, V \}$$

11 I.2 8 either the co-pol nulls

12 I.2 9 al., 1966/1968/1981; Boerner, 1984

13 1.2.2 18 Kanareykhin et al, 1966, 1968, 1981).

13 equation (1.2.15)

$$[\Gamma(m, \gamma)] = m \begin{bmatrix} 1 & 0 \\ 0 & \tan^2 \gamma \end{bmatrix} = m/(2\cos^2 \gamma) \begin{bmatrix} 1 + \cos 2\gamma & 0 \\ 0 & 1 - \cos 2\gamma \end{bmatrix}$$

18 1.2.3b 4 be put into the following form (Davidovitz, 1983)

18 equation (1.2.18)

$$P = |\underline{h}[S]\underline{h}|^2 = (\underline{h}[S]\underline{h})(\underline{h}[S]\underline{h})^*$$

18 equation (1.2.19)

$$\underline{h} = h_M \hat{h}_M + h_N \hat{h}_N = h_M e^{j\delta/2} \hat{h}_M + h_N e^{-j\delta/2} \hat{h}_N; h_M^2 + h_N^2 = 1$$

18 equation (1.2.20)

$$P = (h_M^2 s_{MM} + h_N^2 s_{NN}) (h_M^2 s_{MM} + h_N^2 s_{NN}) = h_M^4 s_{MM} + h_N^4 s_{NN} + 2h_M^2 h_N^2 s_{MM} s_{NN} \cos \delta$$

19 equation (1.2.23)

$$\rho_1 = \frac{h_{M1}}{h_{N1}} = \cot(\gamma_1/2) e^{j\delta_1} = \sqrt{\frac{s_{NN}}{s_{MM}}} e^{j\pi/2} \quad \text{and}$$

$$\rho_2 = \frac{h_{M2}}{h_{N2}} = \cot(\gamma_2/2) e^{j\delta_2} = \sqrt{\frac{s_{NN}}{s_{MM}}} e^{-j\pi/2} \quad (1.2.23)$$

19 Figure 1.3c: Correct figure is as follows:

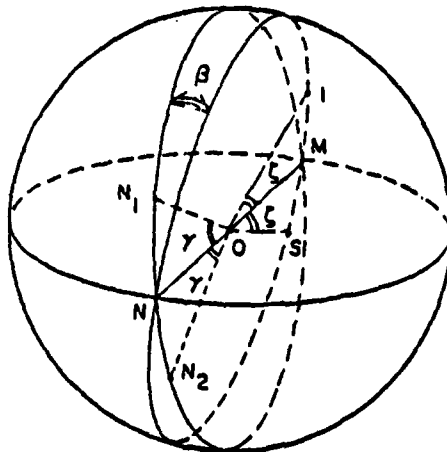


FIGURE 5: Optimum Polarizations Configuration - General Asymmetric Case

N_1, N_2	=	co-pol nulls
I, M	=	cross-pol nulls
γ	=	target characteristic co-pol null angle
δ	=	target characteristic cross-pol null angle
β	=	angle at which the two main circles N_1 - N_2 - M and 1 - M - S - N cut

- 21 1.2.4 8 presented in (Beker and Boerner,
21 1.2.4 13 [S(A, B)]
21 1.2.4 17 several different ways
21 1.2.4 22 (Beker and Boerner, 1983), are satisfied.
21 1.2.4 33 ...measurements alone can determine...
23 1.2.4b2 27 ...is not necessary because $|S_{VV}|, |S_{VV}(90^\circ)| = |S_{HH}(0^\circ)|$.
24 equation (1.2.34)

$$2|S_{45^\circ, V}|^2 = |S_{HV}|^2 + |S_{VV}|^2 + 2|S_{HV}||S_{VV}|\cos(\phi_{HV} - \phi_{VV}).$$

- 30 equation (1.3.9)

$$h_{x'} = h_x \cos \alpha + h_y \sin \alpha$$

$$h_{y'} = h_x \sin \alpha + h_y \cos \alpha$$

- 30 equation (1.3.11)

$$\underline{h}(x', y') = [R(\alpha)]\underline{h}(x, y)$$

- 31 equation (1.3.14/1.3.15)

$$[T] = \begin{bmatrix} e^{j\phi_1} \cos \theta & e^{j\phi_2} \sin \theta \\ -e^{j\phi_3} \sin \theta & e^{j\phi_4} \cos \theta \end{bmatrix}$$

$$[T] = \begin{bmatrix} \cos \theta & -e^{j\xi} \sin \theta \\ e^{-j\xi} \sin \theta & \cos \theta \end{bmatrix} \quad (1.3.15)$$

- 32 equation (1.3.20)

$$[T']_C = 1/\sqrt{2} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}$$

33 equation (1.3.30)

$$\begin{bmatrix} g_0' \\ g_1' \\ g_2' \\ g_3' \end{bmatrix} = (1 + \rho\rho^*)^{-1} \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -j & j & 0 \end{bmatrix} \begin{bmatrix} (h_x h_x^* - \rho^* h_x h_y^* - \rho h_y h_x^* + \rho\rho^* h_y h_y^*) \\ (\rho h_x h_x^* + h_x h_y^* - \rho^2 h_y h_x^* - \rho h_y h_y^*) \\ (\rho^* h_x h_x^* - \rho^*{}^2 h_x h_y^* + h_x^* h_y^* - \rho^* h_y h_y^*) \\ (\rho\rho^* h_x h_x^* + \rho^* h_x h_y^* + \rho h_y h_x^* + h_y h_y^*) \end{bmatrix}$$

35 1.3.3c 25 ...in circular polarization basis ($\rho = -j$) is

40 1.3.5b 3/4 Also, from (1.3.62), the trace

$$\text{Tr}\{[P]\} = |S_{HH}|^2 + |S_{VV}|^2 + 2|S_{HV}|^2 = \text{span}\{[S]\} = p$$

41 equation (1.3.69a)

$$[S(HV)]_{\text{SMR}} = \begin{bmatrix} |S_{HH}| e^{j(\phi_{HH} - \phi_{HV})} & |S_{HV}| \\ |S_{HV}| & |S_{VV}| e^{j(\phi_{VV} - \phi_{HV})} \end{bmatrix}$$

44 missing references

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46 equation (1.4.2)

$$\vec{J}(\vec{r}, t) = \vec{J}_{po}(\vec{r}, t) + \vec{J}_e(\vec{r}, t), \quad \text{with}$$

$$\vec{J}_e(\vec{r}, t) = \frac{1}{2\pi} \iint_S \hat{a}_n \times \{L\vec{J}(\vec{r}', \tau) \times \hat{a}_R\} ds'$$

49 equation (1.4.14)

$$D_\psi = \frac{-k^4}{4\pi^2} |A(k)|^2 \left(\frac{K_u - K_v}{2k} \right) \cos 2\alpha$$

52 1.5 27 ...approach of Chew, (1966) and Dolph & Chow, (1980) ...

57 1.5.4 4-7

Taking the total derivatives with respect to the parameter α :

$$\frac{dS_n}{d\alpha} = \frac{-\frac{\partial}{\partial \alpha} \langle L f_n, h_n \rangle}{\frac{\partial}{\partial S_n} \langle L_n f_n, h_n \rangle}$$

60 1.5.8 19 where \tilde{E}_y is the Laplace Transform...

60 1.5.8 27 We choose, at this point, the input (exciting) waveform.

66 1.6 25 ...introduced in sections 1.2 and 1.3. We thus find:

71 1.6.3 fourth equation

$$[S(H, V)] = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

- 73 1.6.4 3 Matrix Data", in print, IEEE Trans. A&P Society, 1984.
- 73 1.6.4 21 J.R. Huynen, Towards a Theory of Perception for Radar Targets, Proceedings of the NATO-ARW on "Inverse Methods in Electromagnetic Imaging", Sept. 18-24, 1983, Bad Windsheim, FR Germany, Section IV.2, Published by D Reidel Publishing Co., Dordrecht, Holland/Boston, MA.
- 73 1.6.4 26 A.C. Manson and W-M. Boerner, Interpretation of High Resolution Polarimetric Radar Target Down-Range Signatures of Truncated Cylindrical Targets with Attachments, Proceedings of NATO-ARW on "Inverse Methods in Electromagnetic Imaging", Sept. 18-24, 1983, Bad Windsheim, FR Germany, Section III.12, Published by D. Reidel Publishing Co. Dordrecht, Holland/Boston MA.
- 74 1.7 16 ...the Hermitian matrix introduced in Born & Wolf (1965)
- 74 equation (1.7.4)
- $$\mu = |\mu| e^{j\beta} = \frac{J_{12}}{\sqrt{(J_{11}J_{22})^{1/2}}}$$
- 74 1.7 35 ... It has been shown in Born & Wolf (1965) that...
- 75 1.7 4 ...hydrometeor particles (McCormick and Hendry, (1976)...
- 76 1.7.1 3 after equations ...theoretical analyses (McCormick, 1983).
- 76 bottom ...(the circular depolarization ratio) as:...
- 78 1.8 equations (1.8.2/1.8.3/1.8.4) ...small p instead of capital P.
- 79 1.8 13 ...(Plass and Kattawar, 1968; Merchuk et al, 1980)...
- 80 1.8.2 2 ...transfer equation (Pomraning, 1973)...
- 87 1.8.7 6 G.I. Marchuk, G.A. Mikhailov, M.A. Nazaraliev, R.A. Darbinjan, B.A. Kargin, B.S. Elepov, The Monte Carlo Methods in Atmospheric Optics, Springer Verlag, Berlin, Heidelberg/N.Y., 1980.
- 87 1.8.7 10 G.C. Pomraning, Radiation Hydrodynamics, Pergammon Press Ltd., Headington Hill Hall, Oxford, 1973.
- 93 1.10.2 12 ...orthogonal polarizations (here H ≠ 2).
- 99 1.10.5 page 99 & 100

The following expressions relate the scattered Stokes elements to the incident coherency matrix elements and the scattering matrix elements by substituting equations (1.10.15) into the above equation, yielding:

$$\begin{aligned}
 g_{s0} &= \langle [|S_{11}|^2 |E_{i1}|^2 + 2\text{Re}[S_{11}S_{12}^* E_{i1}E_{i2}^*] + |S_{12}|^2 |E_{i2}|^2] \rangle \\
 &\quad + \langle [|S_{22}|^2 |E_{i2}|^2 + 2\text{Re}[S_{22}S_{12}^* E_{i2}E_{i1}^*] + |S_{12}|^2 |E_{i1}|^2] \rangle \\
 g_{s1} &= \langle [|S_{11}|^2 |E_{i1}|^2 + 2\text{Re}[S_{11}S_{12}^* E_{i1}E_{i2}^*] + |S_{12}|^2 |E_{i2}|^2] \rangle \\
 &\quad - \langle [|S_{22}|^2 |E_{i2}|^2 + 2\text{Re}[S_{22}S_{12}^* E_{i2}E_{i1}^*] + |S_{12}|^2 |E_{i1}|^2] \rangle \\
 g_{s2} &= \langle [S_{11}S_{12}^* |E_{i1}|^2 + S_{11}S_{22}^* E_{i1}E_{i2}^* + |S_{12}|^2 E_{i2}E_{i1}^* \\
 &\quad + S_{22}S_{12}^* |E_{i2}|^2] \rangle + \langle [S_{11}^*S_{22} E_{i2}E_{i1}^* + |S_{12}|^2 E_{i1}E_{i2}^* \\
 &\quad + S_{22}^*S_{12} |E_{i2}|^2 + S_{11}^*S_{12} |E_{i1}|^2] \rangle \\
 g_{s3} &= \langle j[S_{11}S_{12}^* |E_{i1}|^2 + S_{11}S_{22}^* E_{i1}E_{i2}^* + |S_{12}|^2 E_{i2}E_{i1}^* \\
 &\quad + S_{22}S_{12}^* |E_{i2}|^2] \rangle - \langle j[S_{11}^*S_{12} |E_{i1}|^2 + S_{11}^*S_{22} E_{i2}^*E_{i1}^* \\
 &\quad + |S_{12}|^2 E_{i1}E_{i2}^* + S_{22}S_{12}^* |E_{i2}|^2] \rangle
 \end{aligned}$$

At this point, it should be noted that, when polarization '1' is transmitted and both '1' and orthogonal '2' are received the scattered Stokes parameters become:

$$\begin{aligned}
 g_{s0} &= \langle |S_{11}|^2 |E_{i1}|^2 \rangle + \langle |S_{12}|^2 |E_{i1}|^2 \rangle \\
 g_{s1} &= \langle |S_{11}|^2 |E_{i1}|^2 \rangle - \langle |S_{12}|^2 |E_{i1}|^2 \rangle \\
 g_{s2} &= \langle S_{11}S_{12} |E_{i1}|^2 \rangle + \langle S_{11}S_{22}^* |E_{i1}|^2 \rangle \\
 g_{s3} &= \langle j[S_{11}S_{12}^* |E_{i1}|^2] \rangle - \langle j[S_{11}^*S_{12} |E_{i1}|^2] \rangle
 \end{aligned}$$

Similarly, when orthogonal polarization '2' is transmitted and both co-polarized '2' and cross-polarized '1' are received, the scattered Stokes parameters become:

$$\begin{aligned}
 g_{s0} &= \langle |S_{12}|^2 |E_{i2}|^2 \rangle + \langle |S_{22}|^2 |E_{i2}|^2 \rangle \\
 g_{s1} &= \langle |S_{12}|^2 |E_{i2}|^2 \rangle - \langle |S_{22}|^2 |E_{i2}|^2 \rangle \\
 g_{s2} &= \langle S_{22}S_{12} |E_{i2}|^2 \rangle + \langle S_{22}S_{12}^* |E_{i2}|^2 \rangle \\
 g_{s3} &= \langle j[S_{22}S_{12} |E_{i2}|^2] \rangle - \langle j[S_{22}^*S_{12} |E_{i2}|^2] \rangle
 \end{aligned}$$

In general, the 4x4 symmetric average Mueller matrix $[M]$ can be expressed as (please, also refer to equation 1.3.8, page 30 of this report):

$$[G]_s [G]_i^T = [M]$$

where

$$[G]_s = \begin{bmatrix} g_{s0} \\ g_{s1} \\ g_{s2} \\ g_{s3} \end{bmatrix}$$

- 101 1.10.5 3<j[S...
- 113 1.10.14 4 ...polarizations are then formed in...
- 113 1.10.14 9 ...do exist (Stock, 1983; Nespor, Agrawal, Boerner, 1983)...
- 114 1.10.15 5 J.D. Nespor, A.P. Agrawal and W-M. Boerner, "Sensitivity of Optimal Polarization Measurements to the Estimation of Raindrop Shapes", Proc. 21st Conference of Radar Meteorology, American Meteorology Society, Edmonton, Alberta, Canada, Sept. 1983.
- 115 1.11.1 2 developed in our...
- 115 1.11.1 5 ..Technology (May 1983: Boerner, Huynen, Davidovitz, etc.)...
- 116 1.11.3 6 ...research initiating treatise (Vannicola & Lis, 1983/84).
- 116 1.11.4 5 ...Nav-Sea Report by Manson et al (1983)....
- 117 1.11.5.1 1 ...a short, but rather important (the very last)...
- 129 II.1.1 14/15 ...The national radar research efforts must develop a very strong basic research wing and, at the same time...
- 164 III.1 bottom of page ...84-01-05 Sheng-Ming Huang (In preparation),
Extraction of Polarimetric Transient Ramp
Response Signatures from Polarimetric Target
Down Range-Maps for Three-Dimensional Target
Shape Reconstruction



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UIC-EECS-CL-EMID-ARO/EL.83-12-14
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ARO FINAL REPORT
December 14, 1983

POLARIZATION UTILIZATION IN RADAR TARGET RECONSTRUCTION

Contract No.	US ARMY ARO DAAG 29-80-K-0027
Duration:	June 15, 1980 - June 14, 1983
Title:	C. Wide (multi-frequency) Band Relationship of a Target's Character- istic Operators and Co/Cross-Polar- ization Null Descriptors with Its Unique Set of Natural Eigenfrequencies.
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(+ dismissed)

IN MEMORIUM

Edward Morton Kennaugh
October 03, 1922 to March 11, 1983



IN APPRECIATION FOR HIS CONTRIBUTIONS TO HIGH RESOLUTION POLARIMETRIC RADAR TARGET HANDLING

- 1949-1954: Kennaugh's Target Characteristic Operator: Polarization Fork
- 1958-1965: Kennaugh's Target Ramp Response Identity
- 1981-1983: Kennaugh's K Pulse Concept



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SYNOPSIS

(Structuring of Final Report)

POLARIZATION UTILIZATION IN RADAR TARGET RECONSTRUCTION
C. Wide (multi-frequency) Band Relationship of a Target's Characteristic
Operators and Co/Cross-Polarization Null Descriptors with its
Unique Set of Natural Eigenfrequencies

In preparing this FINAL REPORT it was considered useful and necessary to provide the Army Research Office, Electronics Division, with a complete overview on what was accomplished during the past four years.

In Chapter I, the background theory is developed comprehensively including the contributions we have made, starting with fundamentals and continuing to more advanced and applied topics, sub-divided into 11 sections. Main references are provided at the end of each section, together with an assessment of our own contributions.

In Chapter II, the state-of-the-art in high resolution radar polarimetry is assessed, recommendations for further extensive studies are made, future trends are assessed, and the benefits for the National Radar Industry in advancing high resolution radar polarimetry are spelled out.

In Chapter III, abstracts of M.Sc./Ph.D. theses carried out during the tenure of this contract are collected. In addition, outlines of ONE-DAY, TWO-DAY and THREE-DAY short courses including references of our short-course material are provided.

In Chapter IV, special citations, editorships, publications and short course presentations are listed. Reprints of papers, reports, etc are available upon request, but are not appended or attached to this Final Report.

In Chapter V, research interaction with DoD-laboratories, the National Radar Industry and those of NATO member countries in good standing are cited by date with identification of contact and topic of mutual interest. It is noted here that these interactive research endeavors constitute one of the main contributions made under this research contract for the U.S. Army Research Office.

In Chapter VI, finally, the description of the development of our own graduate/contract/consulting research facilities is provided together with an outline on near future expansion.

In Chapter VII, the distribution list is presented.

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CHAPTER I

I. BASIC DEFINITIONS, BACKGROUND THEORY, ASSESSMENT OF OUR CONTRIBUTIONS, AND REFERENCES

Synopsis

It is the prime objective of this chapter to provide a succinct overview of the total integral disciplines of high resolution radar polarimetry. First, the definitions for radar target detection, discrimination, classification, imaging and identification are provided, delineating the subtleties of why high resolution radar polarimetry is required for solving some of these problems. Based on this introduction, step-by-step basic principles of radar polarimetry are introduced succinctly amplifying important papers, and assessing our own contributions to the specific subtasks. This chapter will thus serve to assess certain sections in Chapter II, i.e., the current state-of-the-art, fields of applications, recommendations, and benefits for increasing support for the important newly evolving technology of high resolution radar polarimetry. Please note that references will be provided immediately following each section, together with an assessment of our own contributions.

I.0 Introduction

- I.1 Introduction: Basic Definitions of the General Radar Target Recognition Problem Viewed with an Appreciation of High Resolution Radar Polarimetry
- I.2 Basic Principles of Radar Polarimetry: The Coherent Case.
- I.3 Basic Principles of Radar Polarimetry: Mueller Matrix Presentation.
- I.4 Relationships Between Vector Scattering Theory and Polarization Scattering Matrix Characteristics.
- I.5 Broadband Polarimetric Dependencies of a Target's Characteristic Operator with Its Unique Set of Natural Eigenfrequencies.
- I.6 The Received Power: Mueller Matrix Representation and Huynen's N-Target Characteristic Parameter Description.
- I.7 Model-Dependent and Model-Free Radar Clutter Characteristic Theories.
- I.8 Basic Concepts of Polarimetric Vector Radiative Transfer Theory.
- I.9 Application I: Polarimetric Down-range Imaging Using Kennaugh's and Huynen's Target Characteristic Polarimetric Operator Theories.
- I.10 Application II: Model-free Description of Radar Clutter and its Application to Radar Meteorology, Remote Sensing of the Marine/Terrestrial Boundary Layer.
- I.11 Application III: Optimization of Useful Target-Vector Signal vs. Clutter and Noise.

I.0 Introduction

The Electromagnetic Imaging and Geo-electromagnetic Sounding Divisions of the Communications Laboratory, Department of Electrical Engineering and Computer Science, University of Illinois at Chicago, are carrying out extensive research in radar polarimetry. The research is aimed at investigating theoretical and experimental approaches to radar target detection in clutter, target classification, imaging, and identification. A DEC-VAX 11/750 plus 780 Computer System with image processing facilities has been obtained with partial support from the Office of Naval Research. However, no experimental facilities exist at this time to generate the data required for this research, and currently incomplete polarimetric measurement data from various other agencies are being utilized for the research.

In particular we propose to utilize high resolution polarimetric radar data which can be collected with the Broadband Polarization Radar systems of National Radar Laboratories, such as ERADCOM-DELCS-R-T, which should eventually cover the entire m-to-sub-mm wavelength region of the electromagnetic spectrum. In addition, complete high resolution scattering matrix data will also be requested from MICOM-DRSMI-REG and ERIM, Radar & Optics Division; and from polarimetric radar manufacturers such as Martin-Marietta, Aerospace Division; Boeing Aerospace Company, Kent Aerospace Division; Bendix-GSD; Westinghouse DSC-AESD; General Dynamics, Pomona Advanced Technology and Convair (San Diego) Divisions, Honeywell SRC, and General Electric MESO-ADE with whom we have already established and/or will in the near future establish proprietary polarimetric measurement data exchange agreements.

For detailed description of our research efforts we refer to the material previously forwarded to ARO-Electronics Division on

"Advancement of High Resolution Radar Polarimetry in Target vs. Clutter Detection Discrimination, Classification, Imaging and Identification" containing three parts:

PART A: Basic Concepts of Radar Polarimetry: Theory, Metrology, N-Dim Signal Processing, N-Dim Image Processing, Polarimetric Radar Hardware Design

PART B: Our Contributions to Radar Polarimetry (CL-EECS-UIC)

PART C: Recommendations for New Research in Radar Polarimetry - Benefits for a national research effort. (Note, Subsection C.4 "Partition of Task Efforts" provides the logical interpretation of the hows and whys of separating the total effort.

With the support of DoD contracts, a center of excellence for research in radar polarimetry has been set up within the Electromagnetic Imaging Division (EMID), Communications Laboratory (CL), Department of Electrical Engineering and Computer Science (EECS), University of Illinois at Chicago (UIC) with the express purpose of analyzing theoretical, computational and experimental approaches to radar target detection in clutter, separation of useful target signal from noise and clutter; classification of targets and/or clutter; target and/or clutter imaging, as well as target identification.

I.1 INTRODUCTION: BASIC DEFINITIONS OF THE GENERAL RADAR TARGET
RECONSTRUCTION PROBLEM VIEWED WITH AN APPRECIATION OF HIGH
RESOLUTION RADAR POLARIMETRY

In recent years, there has been a rapidly expanding volume of research from both a theoretical and experimental point of view, directed toward the determination of the characteristic properties of radar targets through the use of polarization. The fact that makes this type of investigation possible is that the scattering properties of radar targets are dependent on the polarization of the incident wave. It has also been demonstrated that the interaction of electromagnetic waves with a geometrically bounded material body may best be described as a "Polarization-Sensitive Scatterer Feature Spatial and Temporal Resonance Phenomenon", particularly when the spatial and temporal periods become of the order of the target characteristic features and motional dimensions. Specifically, for the limited data, non-cooperative target case, there exists an hierarchy in complexity, amount, quality and accuracy of radar data required to obtain an "immediate (instantaneous) decision operator" in tactical (seeker) radar for the distinct radar problems of:

1.1.1 Target vs. clutter discrimination: Various methods may be applicable, yet we found that in a hostile clutter and/or chaff environment such as (i) the marine ocean boundary layer, (ii) the atmospheric ground based battlefield scene, or (iii) for low-flying tactical aircraft involved in support of ground/sea-based actions, we must incorporate complete CW polarimetric target/clutter scattering matrix information. Specifically, we require to utilize the dynamic polarimetric fork properties. Whereas, for distributed clutter/chaff, the vector scattering centers are distributed more densely and separated by a small fraction of a wavelength, resulting in a more stable motion of the associated co-polarization nulls (prongs of polarization fork) on the Poincaré sphere; those of isolated larger, more complex (man-made) objects are separated by distances being comparable to the wavelength and larger, resulting in a rapid circular path loci motion on the polarization sphere. Therefore, the highly varied behavior of the dynamic polarization fork motions of the target (rapid) vs. clutter/chaff (slow) on the polarization sphere will provide an indispensable target vs. clutter/-chaff discrimination operator as was demonstrated without further doubt by Poelman (1976 to 1983). We note that we also will need to reassess the merit factor definitions of optimal target signal vs. clutter-plus-noise separation which need to be based on Huynen's N-target theories (Huynen, 1978) and Poelman's (1981) maximum entropy approach for extracting the most useful stochastic merit factor parametric diagrams based on Kennaugh's optimal target polarization null theory (Kennaugh 1949-1954, 1952, 1955-1957; i.e., the Swerling Models require a revision).

1.1.2 Target-vs. target and clutter-vs. clutter classification: Because of the fact that the vector scattering centers of larger, more complex isolated targets are separated by longer electric lengths resulting in rapid circular path motion of the polarization fork, in general, over the entire Poincaré sphere in case of "not-symmetrical" reciprocal targets, we find that a monochromatic CW, limited-aspect, complete polarimetric approach for the backscatter (monostatic) radar case will not suffice; and, in addition, we require polarimetric target downrange silhouette resolution. Although the mean optimal polarization null locations and their spread can be obtained for clutter and/or chaff rather accurately if the polarimetric clutter matrix information is recovered within time frames lying below the clutter vector scattering center reshuffling time; improved clutter classification

(surface vs. inhomogeneous volumetric underburden scatter) can only result from broadband complete polarimetric clutter information (Fung and Eom, 1982, 1983; Morgan and Weisbrod, 1982; McCormick and Hendry, 1982; Mieras et al, 1982; Nespor, Agrawal, Boerner, 1983; Stock 1983).

We re-emphasize that given complete broadband polarimetric scatter matrix information, target classification for the non-cooperative target vs. target, target vs. clutter, and clutter vs. clutter case is possible (Root, 1981, 1983; Boerner, 1984).

1.1.3 Target imaging in inhomogeneous media and/or clutter environments: In case the target does not possess rotational symmetry, but is of general "not-symmetrical" reciprocal shape in addition to complete polarimetric downrange linear chirp maps along the rotational axis of invariance, we will require such data over a wide cone of the unit sphere of directions in dependence of data completeness, quality, etc., or additional "equivalent a priori" target shape information. In case the target is embedded in weakly diffracting clutter, the G.O.-superlimited parallelbeam methods of projection tomography do not suffice; then we must, at least, incorporate back-propagation tomographic methods based on the Born/Rytov approximation to apply, which represents a dramatic improvement over Radon's single ray (straight or bent) projection reconstruction theory. Furthermore, as we are strictly dealing with an electromagnetic vector inverse problem, the scalar back-propagation tomographic method must be extended to vector back-diffraction tomography for the general case of a target embedded in the type of clutter described above. For the application of general vector back-diffraction tomography to target imaging in dense depolarizing clutter, we also must develop direct scattering theories incorporating a polarimetric vector radiation transfer approach utilizing a Stokes' vector formulation which implicitly must also contain multi-scatter phase information (Khounsary and Boerner, 1984; Yang and Boerner, 1984).

1.1.4 Target identification: Complete target identification in shape and material decomposition will strictly require solutions to all of the above three tasks, plus incorporation of complete doppler and scatterometric information within the various windows of the m-to-sub-mm wavelength region. Therefore, we need to develop complete polarimetric broadband (compression pulse) doppler radar systems within the various windows of the 1-400 GHz electromagnetic spectral region so that optimal target information can be extracted from electromagnetic wave/target interaction which is a "polarization-sensitive target feature spatial and temporal resonance phenomenon", i.e., amplitude, phase polarization, frequency, doppler information, all are equivalently and equally important and must be used in singularity.

1.1.5 Criteria for the Assessment of Available Complete Polarimetric Measurement Methods: The main obstacle towards realizing incorporation of complete polarimetric radar target theory into target vs. clutter discrimination, target vs. target classification, target in clutter imaging, single target identification until recently was the underdeveloped state of broadband polarimetric antenna theory and design. It was not possible to recover for the general not-symmetrical reciprocal target case (which must be the basic requirement here), i.e., both amplitude and relative polarization phase of the scattering matrix elements at time frames below the vector scattering center reshuffling time of clutter/chaff. Until very recently, complete ellipsometric amplitude-only measurement principles had to be used which require nine rather time-consuming independent amplitude-only measure-

ments for a selected set of linear, circular and elliptical base polarizations. For the complete symmetric (H,V aligned) target case, Copeland (1960) and Huynen (1960) independently developed polarization rotation-sweep techniques, which were shown to be sufficient to recover the optimal polarization nulls of aligned, symmetric targets only on the polarization sphere from co-polarized amplitude-only measurements. In a next step, a method of recovering the co/cross-polarization phase ϕ_{AB} or ϕ_{BA} for S_{AA}/S_{AB} or S_{BB}/S_{BA}

measurements was developed using fast magnetic waveguide switches and/or pin-diode switches. This method, when redesigned for the circular left/-right polarization base vector pair does provide a two-step complete measurement approach (as e.g. was developed by McCormick/Allan/Hendry (1977-1982) for polarimetric radar meteorology), for which target reciprocity must apply, as well as complete target symmetry with respect to the linear H,V polarization basis which certainly is a rather unrealistic assumption for the case of tactical target detection in meteorological clutter. More recently with the advanced pin-diode switching technology, it is now possible to recover complete polarimetric scattering matrix information for the general "non-symmetrical" reciprocal target case within the time frames which lie below the reshuffling time of vector clutter scattering centers, i.e., we are now witnessing the realistic phase of incorporating complete radar polarimetric concepts into the general radar target description problem.

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1.2 BASIC PRINCIPLES OF RADAR POLARIMETRY: THE COHERENT CASE

In conventional radar systems, the emphasis has been placed on the measurement of the amplitude and frequency and/or phase of the returned echo to derive such parameters as the size, distance and movement of the target. One of the most significant developments of the last decade has been the realization that the polarization of the transmitted and received radar signals in the m-to-mm wavelength regions contain invaluable information about target geometry and material decomposition. Radar polarimetry addresses itself to this question. It has been shown that a single scalar number is not adequate to represent the radar cross section of a target, in as much as this number is highly dependent upon the polarization of the transmitted signal and the orientation of the target with respect to the polarization (Sinclair 1950). The complete scattering description of a target is obtained in terms of its "scattering matrix" which relates the polarization of the scattered wave to that of the incident wave (Kennaugh 1949-1983). If the wave incident on the target is expressed in terms of two orthogonal polarized components, say linear horizontal and vertical, for example, then the wave scattered by the target is expressed in terms of the incident wave as follows (see Figure 1.1):

$$\begin{bmatrix} E_h^s \\ E_v^s \end{bmatrix} = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix} \quad \text{or} \quad \underline{E}^s = [S] \underline{E}^i \quad (1.2.1)$$

where

$$\begin{aligned} \underline{E}^i &= E_h^i \hat{h}_h + E_v^i \hat{h}_v \\ \underline{E}^s &= E_h^s \hat{h}_h + E_v^s \hat{h}_v \end{aligned} \quad (1.2.2)$$

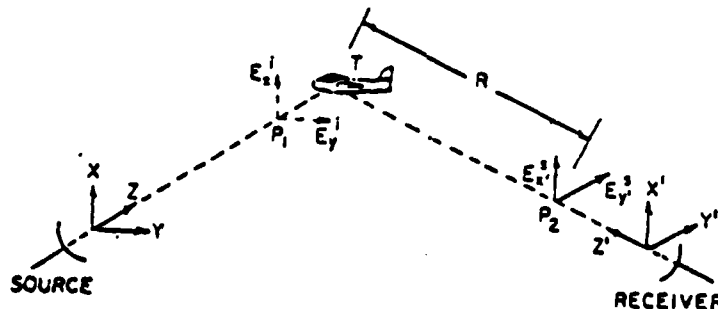


FIGURE 1.1: BISTATIC RADAR SCATTERING GEOMETRY

The scattering matrix $[S]$ is a characteristic of the target. In a monostatic radar, where only backscattering is of significance, and the propagation operator is reciprocal, the scattering matrix is symmetric, i.e., $S_{hv} = S_{vh}$. The elements of the scattering matrix are, in general, complex and hence, six numbers represent the complete backscattering matrix of a target. This is called the scattering matrix with absolute phase. In general, only relative phase measurements are of significance and hence, the phase of one of

the elements (usually that of S_{hv}) is taken as zero. The "relative phase scattering matrix" is thus characterized by five real numbers. This relative phase scattering matrix, which can be expressed in terms of any orthogonal polarization base vector pair (h_A, h_B), constitutes a complete description of the target backscattering properties for a given frequency and a given aspect angle. These are properties of the target alone, independent of the measuring system (Kennaugh 1949-1954, 1955-1957).

For the purpose of further target characteristic discription we will introduce here the following definition of the polarization vector $\underline{h}(a, \alpha, \phi, \tau)$ in terms of the geometrical parameters

$$\underline{h}(a, \alpha, \phi, \tau) = ae^{i\alpha} \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} \cos \tau \\ i \sin \tau \end{bmatrix} \quad (1.2.3)$$

where a is the wave amplitude, α the absolute phase factor, ϕ the polarization orientation angle and τ the polarization ellipticity angle. Note, in representing the polarization state \underline{h} on the polarization sphere, the absolute phase angle cannot be presented as shown in Table 1 where a summary on the basic definitions of the polarization and its representations is given (Huang, M.Sc. thesis, 1984)

Laboratory experiments carried out during the last decade have clearly demonstrated the significance of the scattering matrix as the complete descriptor of a target's scattering characteristics. Thus, a polarimetric radar capable of measuring the scattering matrix is the first step in the improved characterization of the clutter and/or target signatures. This has immediate applications to the improvement of target/clutter ratio, target vs. target and clutter vs. clutter classification, target imaging in homogeneous and/or cluttered environments, and target identification (Lempkowski, M.Sc. thesis, 1984).

1.2.1 New Radar Concepts

Detailed studies of the significance of polarization and the scattering matrix have given rise to new concepts in radar design which adds significantly to the versatility of the radar as a tool for target detection/classification/identification/imaging, optimal detection of target in clutter, and in remote sensing. The basic ideas for this work were proposed in the 1950's first by Kennaugh, his student, Copeland (1958), and later extended by Huynen (1970). The elements of the scattering matrix are dependent upon the basis vectors used to specify the polarization of the incident and scattered fields. If a change is made from one set of orthogonal basis vectors to another set, the new scattering matrix $[S']$ can be obtained from the old matrix $[S]$ by the following relation

$$[S'] = [T]^T [S] [T], \quad (1.2.4)$$

where

$$[T] = \frac{1}{\sqrt{1+\rho\rho^*}} \begin{bmatrix} 1 & -\rho^* \\ \rho & 1 \end{bmatrix}, \quad [S'] = \begin{bmatrix} S'_{AA} & S'_{AB} \\ S'_{BA} & S'_{BB} \end{bmatrix} \quad (1.2.5)$$

which is a unitary transformation matrix such that

$$[T]^{-1} = [T^*]^T. \quad (1.2.6)$$

TABLE 1: POLARIZATION DESCRIPTORS

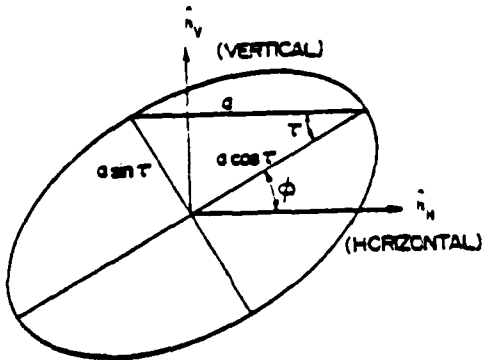
PARAMETER	DEFINITION
a. <u>Radar Cross Section</u>	
i) <u>no polarization correction</u>	$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{ \underline{E}^S ^2}{ \underline{E}^I ^2} = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{ \underline{H}^S ^2}{ \underline{H}^I ^2} \quad (T.1)$
ii) <u>with polarization correction</u>	$\sigma^{rt} = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{ \underline{h}^r \cdot \underline{E}^s ^2}{ \underline{h}^t ^2} \quad (T.2)$
b. <u>The Polarization Vector</u>	
i) <u>time domain</u>	$\underline{h}(t) = a_H \cos \omega t \hat{h} + a_V \cos(\omega t + \delta) \hat{h}_V$ where $\delta = \delta_V - \delta_H$ (T.3)
ii) <u>frequency domain</u>	$\underline{h}(t) = \text{Re}\{\underline{h} e^{j\delta t}\}, \text{ where}$ $\underline{h} = a_H e^{j\delta_H} \hat{h}_H + a_V e^{j\delta_V} \hat{h}_V$ (T.4)
iii) <u>geometric parameter</u>	$\underline{h} = a \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\tau \\ j\sin\tau \end{bmatrix} e^{j\alpha} \quad (T.5)$
iv) <u>polarization ratio</u>	$\underline{h} = a_H e^{j\delta_H} (\hat{h}_H + \rho \hat{h}_V), \text{ where } \rho = \frac{a_V}{a_H} e^{j\delta} \quad (T.6)$
c. <u>The Polarization Ellipse</u>	$\left[\frac{h_H}{a_H} \right]^2 + \left[\frac{h_V}{a_V} \right]^2 - 2 \left[\frac{h_H}{a_H} \right] \left[\frac{h_V}{a_V} \right] \cos\delta = \sin^2\delta$ <div style="display: flex; align-items: flex-start;">  <div style="margin-left: 20px;"> <p>Linear: $\delta = 0$, horizontal ($a_V = 0$)</p> <p>Vertical: ($a_H = 0$), linear 45° ($a_H = a_V$) (T.7)</p> <p>Left Circular (LC): $\delta = 90^\circ$, $a_H = a_V$</p> <p>Right Circular (RC): $\delta = 90^\circ$, $a_H = a_V$</p> <p>Left Elliptic: $\sin\delta > 0$</p> <p>Right Elliptic: $\sin\delta < 0$</p> </div> </div>

TABLE 1: POLARIZATION DESCRIPTORS

d. The Stokes Vector

$$\underline{g} = \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} |h_H|^2 + |h_V|^2 \\ |h_H|^2 - |h_V|^2 \\ 2\text{Re}\{h_H h_V^*\} \\ -2\text{Im}\{h_H h_V^*\} \end{bmatrix} = \begin{bmatrix} a_H^2 + a_V^2 \\ a_H^2 - a_V^2 \\ 2a_H a_V \cos\delta \\ 2a_H a_V \sin\delta \end{bmatrix} = \begin{bmatrix} a^2 \\ a^2 \cos^2\tau \cos^2\phi \\ a^2 \cos^2\tau \sin^2\phi \\ a \sin^2\tau \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad (\text{T.8})$$

where

$$g_0^2 = g_1^2 + g_2^2 + g_3^2 = I^2 = Q^2 + U^2 + V^2$$

$$\text{H: } \underline{g} = \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \text{ V: } \underline{g} = \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \text{ LC: } \underline{g} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \text{ RC: } \underline{g} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}$$

$$\text{Modified Stokes Vector } \underline{g}_m = \left\{ \frac{1}{2}(1+Q), \frac{1}{2}(1-Q), U, V \right\}$$

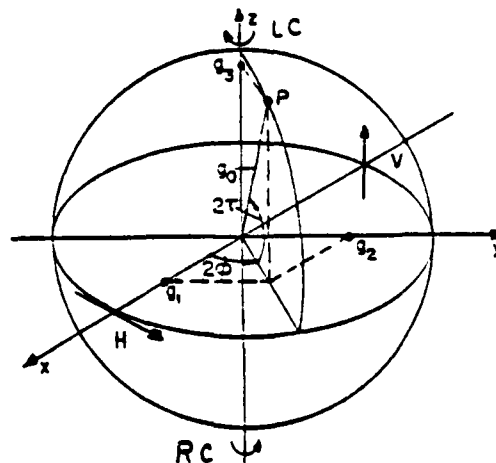
e. The Polarization Ratio

$$\rho = \frac{h_V}{h_H} = \left[\frac{a_V}{a_H} \right] e^{j\delta} = \tan\tau e^{j\delta} \quad (\text{T.9})$$

Linear: $\text{Im}\{\rho\} = 0$, H: $\rho = 0$, V: $\rho = \infty$ Circular: $\text{Re}\{\rho\} = 0$, LC: $\rho = j$, RC: $\rho = -j$ Elliptic: Left elliptic: $\text{Im}\{\rho\} > 0$, right elliptic: $\text{Im}\{\rho\} < 0$ f. The Poincaré Spherei) Cartesian Coordinates = (g_1, g_2, g_3) ii) Spherical = $(g_0, \frac{\pi}{2} - 2\tau, 2\phi)$

iii) In terms of Polarization ratio

$$u = \frac{1-j\rho}{1+j\rho}, \quad \theta = \cos^{-1} \frac{|u|^2 - 1}{|u|^2 + 1}, \quad \phi = \text{phase}(u) \quad (\text{T.10})$$

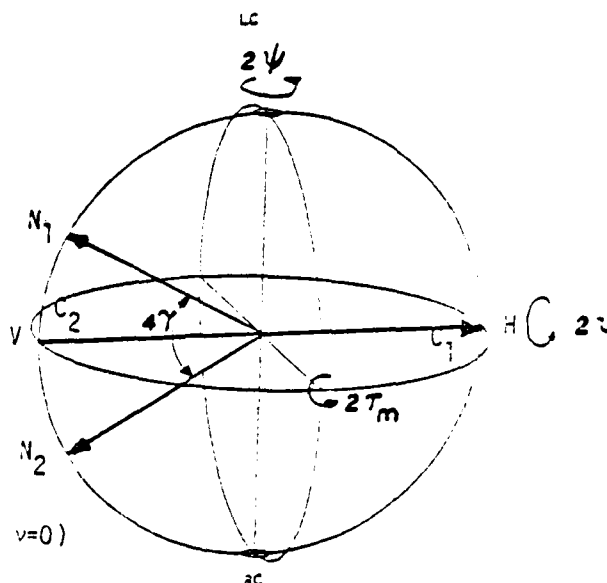
THE POLARIZATION SPHERE
(Poincaré)

Here, ρ is a complete transformation parameter which relates the two sets of basis vectors. It turns out that $[S']$ is symmetric if $[S]$ is symmetric. Furthermore, there are special sets of optimal polarization vectors, and corresponding values of ρ , which make either $S'_{A'A'}$ and $S'_{B'B'}$ equal to zero or $S'_{A'B'}$ and $S'_{B'A'}$ equal to zero (see M.Sc. theses of Chan (81), Foo (82), Saatchi (83), Davidovitz (83)). The former are called "co-pol nulls" and the latter, "cross-pol nulls". The values of ρ , which will give rise to either. The co-pol nulls or cross-pol nulls, are easily obtained in terms of the elements of the scattering matrix $[S]$:

$$\begin{aligned} S'_{A'A'} &= (1 + \rho\rho^*)^{-1} [S_{AA} + \rho^2 S_{BB} + \rho(S_{AB} + S_{BA})] \\ S'_{A'B'} &= (1 + \rho\rho^*)^{-1} [-\rho^* S_{AA} + S_{BB} + S_{AB} - \rho\rho^* S_{BA}] \\ S'_{B'A'} &= (1 + \rho\rho^*)^{-1} [\rho^* S_{AA} + S_{BB} - \rho\rho^*(S_{AB} + S_{BA})] \\ S'_{B'B'} &= (1 + \rho\rho^*)^{-1} [\rho^* S_{AA} + S_{BB} - \rho^*(S_{AB} + S_{BA})] \end{aligned} \quad (1.2.7)$$

Thus, these nulls are uniquely related to the target. If the polarization is expressed as a point on the Poincaré Sphere, then the cross-pol nulls are anti-podal and the two co-pol nulls are equi-distant from, and on opposite sides of the minor cross-pol null. Thus, a target carries a unique signature in terms of the location of its co-pol and cross-pol nulls on the Poincaré Sphere. These nulls constitute Kennaugh's Target Characteristic Operator also known as "Polarization Fork" (see Figure 1.2); and a knowledge of either both the co-pol nulls or one co-pol and one cross-pol is adequate to completely specify the scattering matrix of the target for one aspect and at one frequency.

$$\begin{aligned} 0 &< \gamma < 45^\circ \\ -45^\circ &< \nu < 45^\circ \\ -45^\circ &< \tau_m < 45^\circ \\ -90^\circ &< \psi < 90^\circ \end{aligned}$$



(Illustrated for $\psi=90^\circ$, $\tau_m=0$, $\nu=0$)

FIGURE 1.2: KENNAUGH'S TARGET CHARACTERISTIC OPERATOR:
THE POLARIZATION FORK (Huynen 1982)

It should be noted that the co-pol and x-pol nulls lie on one main circle on the Poincaré Sphere and that their locations define the polarization fork (Figure 1.2). The x-pol nulls are anti-podal on this sphere, and the line joining them bisects the angle between the co-pol nulls as shown in Figure 1.2. We note here that this unique description of a scatterer under monostatic conditions given for one frequency and aspect is of paramount importance to target description at one aspect and one frequency, and its properties have been overlooked in practice (Kennaugh, 1949-1952; Kanareykin et al., 1966/1968; Boerner, 1984 a/b; Cloud, 1983; Varganov, Zinov'ev and Kanareykhin, 1984).

The unitary transformation presented above satisfies the following invariants:

$$\det\{[S'(A', B')]\} = \text{invariant when } \det\{[T]\} = \pm 1, \quad (1.2.8)$$

otherwise, $\det\{[S'(A', B')]\}$ is different by a factor of $\exp(2\text{ARG}\{\det[T]\})$ and

$$\text{Span}\{[S(A, B)]\} = |S_{AA}|^2 + |S_{AB}|^2 + |S_{BA}|^2 + |S_{BB}|^2 = p \quad (1.2.9)$$

$$\begin{aligned} &= \text{Span}\{[S'(A', B')]\} = |S'_{A'A'}|^2 + |S'_{A'B'}|^2 + |S'_{B'A'}|^2 + |S'_{B'B'}|^2 \\ &= \text{invariant.} \end{aligned}$$

We note that if $S_{AB} = S_{BA}$, then $S'_{A'B'} = S'_{B'A'}$ for all p ; i.e., if reciprocity is satisfied for any one pair of orthogonal polarizations, it is satisfied for all such pairs. Furthermore, we must emphasize the important property that for any one given aspect and for one frequency, the transformation is polarization invariant, i.e., the transformation occurs on one and the same polarization sphere of radius $p = \text{span}\{[S(A, B)]\}$. Thus, if $[S(A, B)]$ is known and reciprocity, as well as conservation of energy is satisfied, $[S'(A', B')]$ for any other orthogonal pair $h(A', B')$ can be obtained as is shown, for example, for the transformation from linear to circular polarization base vectors in Boerner (1982). In case of polarization losses, properties of the coherency matrix need to be used (Thiel, 1968), and the transformation will not occur on the same polarization sphere (Deschamps, 1953; Deschamps and Mast, 1973).

The span invariant plays a very important role in cross-range formation, using data recovered from dual polarization SAR/RAR or, microwave holographic imaging methods. Whereas, in recent partial polarimetric SAR/RAR image evaluation, only $|S_{HH}|^2$, $|S_{VV}|^2$ or $|S_{HV}|^2$ had been recorded and rarely superimposed, we must emphasize here that it is essential and absolutely necessary to record total polarimetric information on $[S]$, i.e., amplitude and relative polarimetric phase and to provide incoherently superimposed images for the σ_{HH} , σ_{VV} and $\sigma_{HV} = \sigma_{VH}$ returns according to the span invariant

$$p = \text{span}\{[S(A, B)]\} = |S_{AA}|^2 + |S_{BB}|^2 + 2|S_{AB}|^2 \quad (1.2.10)$$

which is polarization invariant and contains complete cross-range image information. Incomplete "polarization diversity" approaches such as recording

of either $|S_{AA}|^2$, $|S_{AB}|^2$ and/or $|S_{BB}|^2$ are incomplete and will result in the loss of information. In the following two figures (Figures 1.3 a and b) obtained from complete polarimetric RAR laboratory set-ups, it is clearly demonstrated how the image fidelity, feature enhancement, resolution and image quality is increased by superimposing the three independent scattering matrix components for linear H, V polarization bases incoherently.

1.2.2 Kennaugh's Target Characteristic Operator Theory

Based on the inspiration of Sinclair (1949, 1950) in a series of papers on radar antenna polarization (Runsey et al, 1951), and on the important pioneering studies of Kennaugh (1949 to 1952) and Gent (1954), an early attempt at single radar target classification was made by Copeland (1960) using the received complex voltage with rotating linear polarization illumination. This concept was further advanced by Huynen (1970), who expanded on the measurement conceptual studies on $[S]$, by Graves (1956), and Maffett (1968). A significant summary of the early state-of-the-art of radar measurements was presented at the Radar Reflectivity Measurement Symposium 1964, in a subsequent Special IEEE Proceedings issue on Radar Reflectivity Studies, and further developed in the Russian literature (Kanareykin et al, 1966, 1968). Of particular interest is the theory of radar target phenomenology developed by Huynen (1970) utilizing the deterministic polarization-agile characteristics of isolated single targets contained in $[S]$ which was first developed by Kennaugh (1952) who introduced a set of five independent canonical target discriminant parameters: the target orientation angle ψ , the ellipticity angle τ_m of maximum target polarization, the relative polarization phase expressed in terms of the target skip angle ν , the target characteristic identification angle γ , and the target characteristic magnitude m (See Figure 1.2), and in addition, the absolute phase α may be defined. Introducing the rotational group or Pauli spin matrices $[J]$, $[K]$, and $[L]$ related to the unit matrix $[I]$ as shown in (Huynen, 1970) by

$$[J]^2 = -[I], [K]^2 = -[I], [L]^2 = -[I] = [J] \cdot [K] = [K] \cdot [J], \quad (1.2.11)$$

where

$$[I] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, [J] = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, [K] = \begin{bmatrix} 0 & i \\ i & 0 \end{bmatrix}, [L] = \begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix} \quad (1.2.12)$$

it can be shown for $\alpha = 0$ that $[S]$ becomes

$$[S] = [U^*(\psi, \tau_m, \nu)] [\Gamma(m, \gamma)] [U(\psi, \tau_m, \nu)]' \quad (1.2.13)$$

where $[U]'$ denotes the transpose of $[U]$, and

$$[U(\psi, \tau_m, \nu)] = \exp(\psi[J]) \exp(\tau_m[K]) \exp(\nu[L]) \quad (1.2.14)$$

$$[\Gamma(m, \gamma)] = m \begin{bmatrix} 1 & 0 \\ 0 & \tan^2 \gamma \end{bmatrix} = m/2 \cos^2 \gamma \begin{bmatrix} 1 + \cos^2 \gamma & 0 \\ 0 & 1 - \cos^2 \gamma \end{bmatrix} \quad (1.2.15)$$

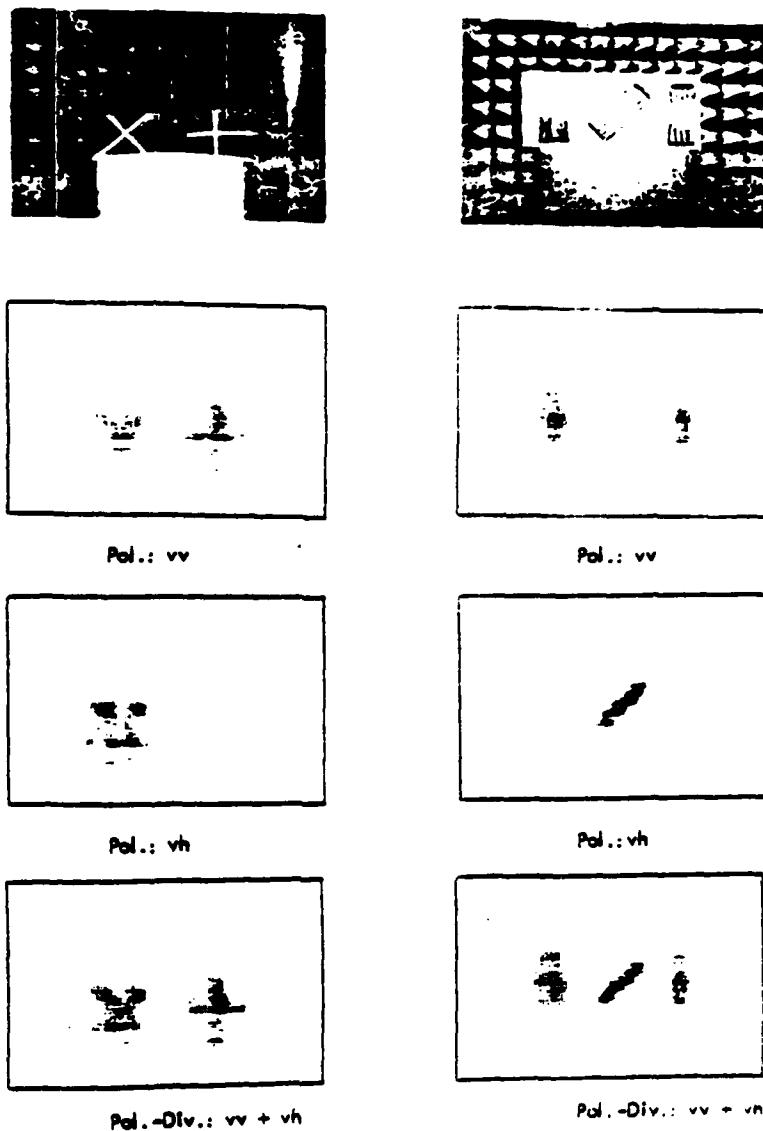
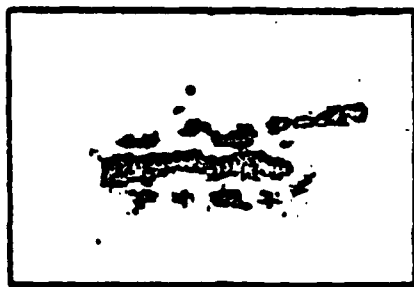
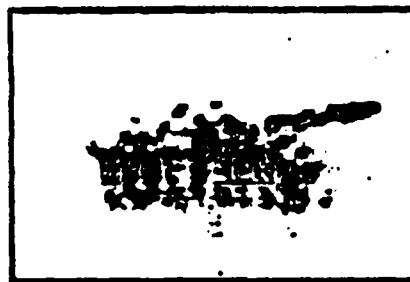


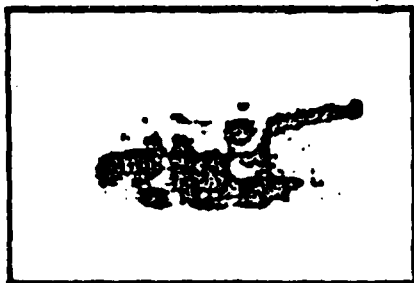
FIGURE 1.3a POLARIZATION EFFECTS ON THE MICROWAVE
IMAGES OF A SIMPLE TEST OBJECT
(Left: flat, plate)
(Right: dihedral corner reflectors)
 $f = 36$ GHz, 3dB resolution = 2, 4λ
(Gniss et al, 1978)



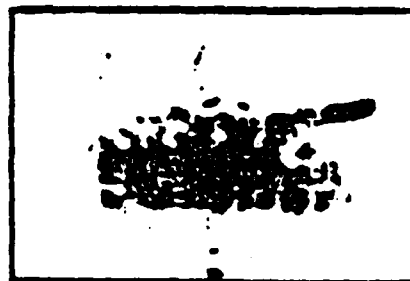
Pol.: vv



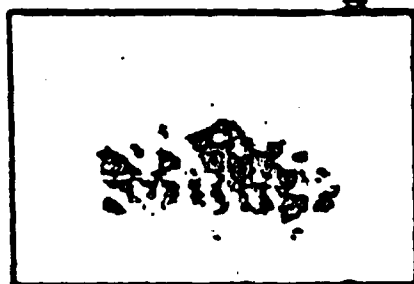
Pol.-Div.: vv + vh



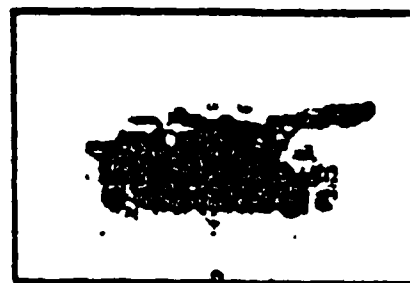
Pol.: hh



Pol.-Div.: hh + vh



Pol.: vh



Pol.- Span: vv + hh + 2vh

FIGURE 1.3b Polarimetric Image Reconstruction according to
Span {[S]} invariant:

$$|S_{opt}|^2 = |S_{AA}|^2 + 2|S_{AB}|^2 + |S_{BB}|^2 = \left| \left(\frac{1}{2\pi} \right)^2 k^4 A_F^2(k) \right|$$

(Magura et al, 1978, "Polarization dependence of image fidelity in microwave mapping systems", '78 Int'l IEEE/AP-S Symposium, Proceedings, pp. 38-41).

The definition of Kennaugh's target characteristic scattering operator shows that $[S]$ can be diagonalized by a unitary transformation matrix, $[U(\psi, \tau_m, \nu)]$, where ψ , τ_m , and ν are Eulerian rotation angles of the sphere about three orthogonal axes as shown in Figure 1.2, and the remaining target characteristic operator $[r(m, \gamma)]$ expresses the properties of the co-polarization null locations in terms of the target characteristic identification angle γ and the target characteristic magnitude m . It has been shown that propagation losses and other relative constant multipliers of $[S]$ can be absorbed in m so that target polarization effects can be determined in terms of the normalized target characteristic operator (Kennaugh, 1952; Huynen 1970, Kennaugh 1981)

$$r(m = 1, \gamma) = \begin{bmatrix} 1 & 0 \\ 0 & \tan^2 \gamma \end{bmatrix} \quad (1.2.16)$$

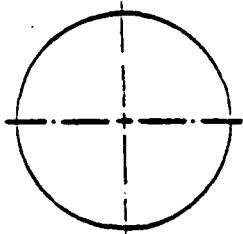
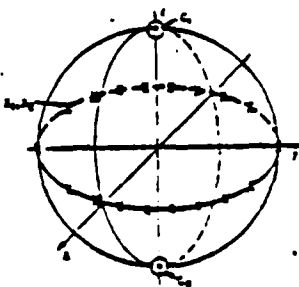
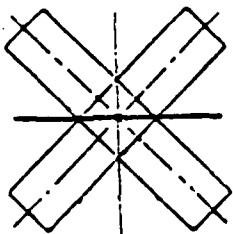
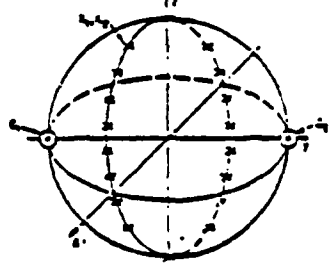
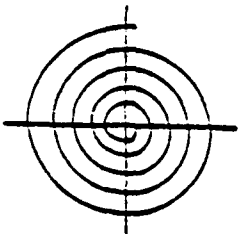
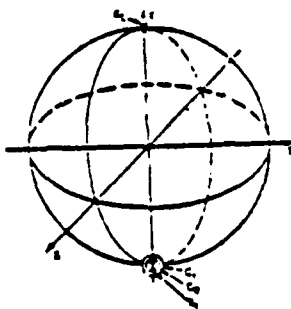
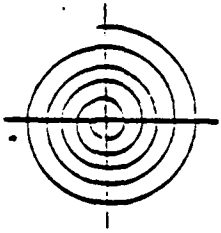
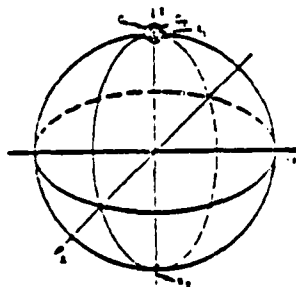
which can be mapped onto the gamma target map of Kennaugh (1952/1981) as is illustrated in Huynen (1970). The peculiar properties of the normalized target characteristic operator $[r(m = 1, \gamma)]$ and of the unitary non-commutative transformation matrix $[U(\psi, \tau_m, \nu)]$ enabled Kennaugh and Huynen to establish the polarization fork concept for single targets, relating the co-polarization null locations (Figure 1.2: N_1, N_2) with an angle of (4γ) between the nulls and the center of the normalized ($m = 1$) sphere. From inspection of Figure 1.2, we observe that the location of the cross-polarization nulls $C_1 = \text{Max}$ and $C_2 = \text{V}$, bisect the angles spanned by N_1 and N_2 , and for symmetric target shapes C_1 and C_2 lie on the equator of the polarization sphere which specifies purely linear polarization. Huynen (1960) provided examples and interpretations for simple canonical target shapes including values for (m, ψ, τ_m, ν) and in Table 2, the co-pol and x-pol null configuration for a number of single target shapes is presented. Summarizing, we note that the polarization fork concept establishes a powerful single target discriminator which provides deep insight into a target's polarization properties (Boerner, 1984).

1.2.3a The Asymmetric Target Case

Consider a stationary target illuminated by a transmitter with adaptive antenna polarization states. The receiver may be situated at the same location as the transmitter (monostatic configuration) or moved to any other preferable location (bistatic configuration: see Figure 1.1). Moreover, it is assumed that the receiver is capable of measuring the complete scattering matrix $[S]$, i.e., it will also require adaptive antenna polarization states. This fact has been overlooked in many recent treatise on the subject matter.

It should be noted that the bistatic scattering matrix will, in general, be non-symmetrical, whereas the monostatic scattering matrix will always be symmetrical, assuming the propagation medium satisfies reciprocity. The analysis will, therefore, be performed for the more general non-symmetrical case. The results for the special symmetrical case will be deduced by simply equating the off-diagonal terms of the scattering matrix.

TABLE 2: CO-POL and X-POL NULL FOR SIMPLE TARGET SHAPES

TARGET	SCATTERING [S] AND MODIFIED MUELLER [M _m] MATRICES	CO-POL (C) AND X-POL (X) NULLS ON POINCARÉ SPHERE
 a. Ideally conducting flat plate or sphere	$[S] = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $[M_m] = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	
 b. Metallic trough	$[S] = \pm \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ $[M_m] = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$	
 c. Metallic helix (right screw)	$[S] = \pm \begin{pmatrix} 1 & -j \\ -j & -1 \end{pmatrix}$ $[M_m] = \pm \begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ -2 & -2 & 0 & -2 \end{pmatrix}$	
 d. Metallic helix (left screw)	$[S] = \pm \begin{pmatrix} 1 & j \\ j & -1 \end{pmatrix}$ $[M_m] = \pm \begin{pmatrix} 1 & 1 & 0 & -1 \\ 1 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 2 & 2 & 0 & -2 \end{pmatrix}$	

1.2.3b Optimal Polarizations for Identically Polarized Transmit-Receive Antennas

By appropriate polarization basis transformation, any asymmetric scattering matrix [S] may be put into the following form

$$[S(M,N)] = \begin{bmatrix} s_{MM} & s_{MN}e^{j\eta} \\ -s_{MN}e^{j\eta} & s_{NN} \end{bmatrix} \quad (1.2.17)$$

where all the quantities denoted by "s" and "η" are positive and real. The basis (M,N) will be termed "characteristic" basis of the scattering operator, as it will be shown to possess many special properties.

The echo area of the target for the case of identically polarized transmit-receive antenna is proportional to the following quadratic form:

$$P = |\underline{h}[S]\underline{h}|^2 = (\underline{h}[S]\underline{h})^* \quad (1.2.18)$$

where \underline{h} is the antenna height and $|\underline{h}| = 1$.

Following Kennaugh (1952) let:

$$\underline{h} = h_M \hat{h}_M + h_N \hat{h}_N = h_M e^{j\delta/2} \hat{h}_M + h_N e^{j\delta/2} \hat{h}_N; \quad h_M^2 + h_N^2 = 1 \quad (1.2.19)$$

Expansion of the expression for P yields

$$P = (h_M^2 s_{MM} + s_{NN}) (h_M^2 s_{MM}^* + h_N^2 s_{NN}) = h_M^4 s_{MM} + h_N^4 s_{NN} + 2h_M^2 h_N^2 s_{MM} s_{NN} \cos \delta \quad (1.2.20)$$

Since s_{MM} and s_{NN} are real, positive quantities, it is clear that P achieves a maximum when $\delta = 0$. Using this fact, and setting the first derivatives of P with respect to h_M and h_N equal zero, the maxima are determined to be

$$\begin{aligned} &h_M = 1, h_N = 0, \delta = 0 \rightarrow P = s_{MM}^2 \quad (\text{Note, the true maximum polarization is either M or N depending on whether } s_{MM} > s_{NN} \text{ or } s_{MM} < s_{NN}) \\ &\text{and } h_M = 0, h_N = 1, \delta = 0 \rightarrow P = s_{NN}^2 \end{aligned} \quad (1.2.21)$$

It is seen, therefore, that the maximum polarizations correspond to the orthogonal polarizations constituting the characteristic (M,N) basis. This in turn means that the maximum polarizations are represented by antipodal points on the Poincaré sphere.

Another set of optimum, in the minimum sense, polarizations can be determined by setting $P = 0$, which yields

$$s_{MM}^2 s_{MM} + h_N^2 s_{NN} = 0 \rightarrow \frac{h_N^2}{h_M^2} = -\frac{s_{NN}}{s_{MM}} \rightarrow \frac{h_N}{h_M} e^{j\delta} = \sqrt{\frac{s_{NN}}{s_{MM}}} e^{\pm j\pi/2} \quad (1.2.22)$$

Denoting the two null polarizations by \underline{h}_1 and \underline{h}_2 , their respective ratios in the (M,N) basis may be given by

$$\rho_1 = \frac{h_{M1}}{h_{N1}} = \cot(\gamma_1/2)e^{j\delta_1} = \sqrt{\frac{s_{NN}}{s_{MM}}} e^{j\pi/2} \quad \text{and}$$

$$\rho_2 = \frac{h_{M2}}{h_{N2}} = \cot(\gamma_2/2)e^{j\delta_2} = \frac{s_{NN}}{s_{MM}} e^{-j\pi/2} \quad (1.2.23)$$

Inspection of the two expressions reveal the following facts:

$$\gamma_1 = \gamma_2 = \gamma \quad \text{and} \quad \delta_1 - \delta_2 = \pi \quad (1.2.24)$$

In terms of the Poincaré sphere representation, the angle γ corresponds to the length of the arc connecting the null polarizations with the point representing the characteristic polarization \hat{h}_M . The angles $\gamma_{1,2}$ correspond to rotations of the sphere about the diameter connecting \hat{h}_M and \hat{h}_N . Consequently, since the difference in the values of these rotations is equal to π , the two null polarizations must be located in the same great circle. Moreover, the fact that $\gamma_1 = \gamma_2 = \gamma$ implies that the angle N_1ON_2 concluded by $N_1(\hat{h}_1)$, the center of the sphere O and $N_2(\hat{h}_2)$ is bisected by the diameter connecting \hat{h}_M and \hat{h}_N and is illustrated in Figure 1.3c.

For the case of a symmetrical operator, and more specifically, for the monostatic arrangement, the method used to obtain the optimum polarizations, as well as the results derived in this section are completely valid.

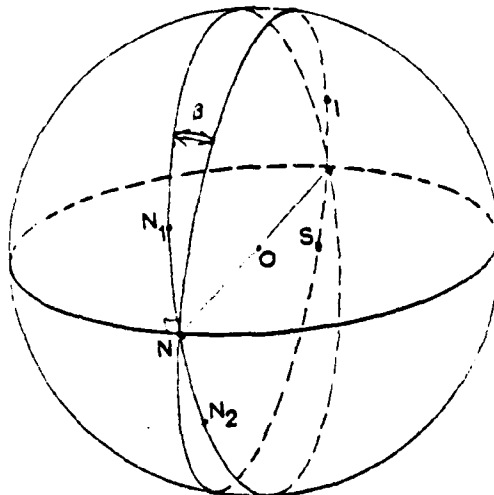


FIGURE 1.3c: Optimum Polarizations Configuration - General Asymmetric Case

N_1, N_2	=	co-pol nulls
I, M	=	cross-pol nulls
γ	=	target characteristic co-pol null angle
ζ	=	target characteristic cross-pol null angle
β	=	angle at which the two main circles N_1-N-N_2-M and $I-M-S-N$ cut

1.2.3c Maximum Return Obtainable with Separately Variable Transmit-Receive Antenna Polarizations

The echoing area of the target obtained with $\underline{h}^t \neq \underline{h}^r$ is proportional to a bilinear matrix form, given by

$$P = |\underline{h}^r[S]\underline{h}^t|^2 = (\underline{h}^r[S]\underline{h}^t)(\underline{h}^r[S]\underline{h}^t)^* \quad (1.2.25)$$

Mathematically speaking, optimization of the above bilinear form is easiest when the matrix $[S]$ is diagonal. The first part of this analysis is, therefore, concerned with diagonalization of $[S]$. The desired result is achieved utilizing a certain theorem found in the theory of finite-dimensional vector spaces. The essential statement of the theorem reads as follows (Davidovitz and Boerner, 1983); (McDuffee, 1956):

Theorem: For any non-singular asymmetric matrix $[S]$, there exist two distinct unitary matrices $[U]$ and $[V]$, such that

$$[U][S][V] = [S_0] \quad (1.2.26)$$

where $[S_0]$ is a diagonal matrix.

Optimization of the bilinear form can now be considered utilizing the diagonal form of the scattering matrix $[S]$. As the results of the optimization procedure indicate, the asymmetry of the scattering matrix $[S]$ introduces an additional pair of physically meaningful optimal polarizations. If the transmitting antenna's polarization ratio is given by ρ_t and the receiving antenna's by ρ_s , where

$$\rho_t^{1,2} = \frac{-b \pm \sqrt{b^2 + r|a|^2}}{2a}; \quad (1.2.27)$$

$$a = (-s_{MM}s_{MN}e^{j\eta} + s_{NN}s_{MN}e^{-j\eta}); \quad b = (s_{MM}^2 - s_{NN}^2)$$

and

$$\rho_s^{1,2} = -\rho_t^{1,2}$$

the maximum target echo is recorded at the receiver. Furthermore, it has been proven that for the asymmetric scattering matrix case, this is the absolute or "global" maximum echo, exceeding that obtained using commonly polarized transmit-receive antennas, i.e., $\underline{h}^t = \underline{h}^r = \hat{h}_M$.

Thus, we observe that great care must be taken in establishing whether the scattering matrix is symmetric, if so, the simplified optimal null theories introduced first by Kennaugh (1952) can be used. From the above analysis, it also follows that, whereas for the symmetric scattering matrix case, five independent parameters will suffice to characterize a target which is uniquely described at one aspect and one frequency; in the general asymmetric case, we require seven independent parameters as was clearly established in the M.Sc. thesis of Davidovitz (1983) and also reported in Davidovitz and Boerner (1983).

1.2.4 Antenna Polarization and Scattering Matrix Measurements in Mixed Polarization Bases

The ambiguity in the sense of polarization measurement, using amplitude measurements only, comes when four antennas, with polarization of each, located in the same great circle on the Poincaré polarization sphere are employed. A mathematical proof of the fact that correct sense of polarization is important to determine when four antenna polarizations in the same great circle on the polarization sphere is presented (Beker and Boerner, 1983). In great detail, the mathematical and physical relationships are derived for the prescription of complete scattering matrix measurements, i.e., what kind of measurements need to be performed for extracting complete polarimetric information so that the relative phase scattering matrix $[S(A,B)]$ for any polarization vector base can be reconstructed. It is the prime objective of this detailed analysis to assist in developing efficient polarimetric radar measurement design concepts.

Measurement of the target scattering matrix $[S(A,B)]$ can be accomplished in several different ways, including such methods as "amplitude-only", "amplitude and partial phase measurements in one orthogonal polarization base $PB(A,B)$ ", or "in mixed orthogonal bases $PBM(A,B; A',B')$ ". It will be shown how the complex elements of the complete relative phase scattering matrix S_{RSM} can be recovered uniquely, provided certain basic conditions which are derived in great detail in (Beker and Boerner 1983).

1.2.4a Antenna Polarization Measurements

a.1 Amplitude-Only: The ambiguity in the sense of polarization measurement, using amplitude measurements only, comes when four antennas, with polarization of each, located in the same great circle on the Poincaré polarization sphere are employed. This particular method, as proposed and implemented by Hollis, Hickman and Lyon (1970) is known as amplitude measurements of multiple components.

a.2 Amplitude and Phase: It was shown by Copeland (1958) that amplitude measurements will introduce ambiguity in the sense; whereas, the phase measurement will yield the correct sense of polarization. The above statement suggests that phase measurements alone can determine the polarization state of an elliptically polarized plane wave (Beker and Boerner, 1983).

1.2.4b Scattering Matrix Measurements

b.1 Amplitude-Only: amplitude only measurements were first considered by Kennaugh in a series of reports at the Ohio State University (Kennaugh 1949-1950) in which he laid out the ground work for further studies.

Consider a transmitted wave \underline{E}^i impinging on the target and scattered in all directions. One of these directions will be back toward the radar where the received signal will be \underline{E}^s . The transmitted and received signals can be related by a scattering matrix $[S]$ (Kennaugh, 1949-1950) as

$$\underline{E}^s = [S] \underline{E}^i \quad (1.2.28)$$

In a linear polarization basis $PB(H,V)$ (H-horizontal, V-vertical), the scattering matrix, for a monostatic case, can be expressed as

$$[S] = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{pmatrix}, \text{ i.e., } S_{HV} = S_{VH} \quad (1.2.29)$$

The elements of $[S]$ are complex quantities having both amplitude and phase; however, if the phase $e^{j\phi_{HV}}$ is factored out, $[S]$ reduces to a relative phase scattering matrix $[S]_{\text{RSM}}$.

One can measure $[S]_{\text{RSM}}$ making amplitude only measurements while rotating the antenna or the target about the line of sight. Seven amplitude measurements are necessary to completely recover the $[S]_{\text{RSM}}$ as was shown by Kennaugh (1949-1950).

The measuring procedure is as follows:

- 1) Measure $|S_{HV}(0^\circ)|$, $|S_{HH}(0^\circ)|$, $|S_{VV}(0^\circ)|$
- 2) Rotate set-up 22.5° and measure $|S_{HV}(22.5^\circ)|$
- 3) Rotate set-up 22.5° further and obtain $|S_{VV}(45^\circ)|$, $|S_{HV}(45^\circ)|$
- 4) Equation (1.2.33) relates measured S_{RR} to linear scattering matrix elements
- 5) Phases $(\phi_{VV} - \phi_{HV})$ and $(\phi_{HH} - \phi_{HV})$ are given by (1.2.30) and (1.2.31), respectively, with sign ambiguities
- 6) Finally, equation (1.2.34) eliminates sign ambiguities.

Step 2) yields one equation with two unknown phases

$$\begin{aligned} & -4|S_{HH}||S_{HV}|\cos(\phi_{HH} - \phi_{HV}) + 4|S_{VV}||S_{HV}|\cos(\phi_{VV} - \phi_{HV}) = \\ & = 8|S_{HV}(22.5^\circ)|^2 - [|S_{HH}|^2 + |S_{VV}|^2 + 4|S_{HV}|^2] + \\ & + 2|S_{HH}||S_{VV}|\cos(\phi_{VV} - \phi_{HH}) \end{aligned} \quad (1.2.30)$$

and

Step 3) given an additional equation containing the two unknowns of (1.2.30)

$$\begin{aligned} & 4|S_{HH}||S_{HV}|\cos(\phi_{HH} - \phi_{HV}) + 4|S_{VV}||S_{HV}|\cos(\phi_{VV} - \phi_{HV}) = \\ & = |S_{HH}|^2 + |S_{VV}|^2 + 4|S_{HV}|^2 + \\ & + 2|S_{HH}||S_{VV}|\cos(\phi_{HH} - \phi_{VV}) - 4|S_{VV}(45^\circ)|^2 \end{aligned} \quad (1.2.31)$$

as well as the phase $(\phi_{VV} - \phi_{HH})$ given by

$$\frac{-4|S_{HV}(45^\circ)|^2 + |S_{VV}|^2 + |S_{HH}|^2}{2|S_{VV}||S_{HH}|} = \cos(\phi_{VV} - \phi_{HH}) \quad (1.2.32)$$

To remove sign ambiguities circularly polarized transmit-receive antenna system should be used. Additional amplitude measurements using right circular antenna for receiving and transmitting yield an equation that resolves sign ambiguities in the phase of (1.2.30) and (1.2.31) since only one choice of $(\phi_{HH} - \phi_{HV})$ and $(\phi_{VV} - \phi_{HV})$ will satisfy

$$S_{RR} = \frac{1}{2} (S_{HH} - S_{VV} + j2S_{HV}) \quad (1.2.33)$$

$$4|S_{RR}|^2 = |S_{HH}|^2 + |S_{VV}|^2 + 4|S_{HH}|^2 - 2|S_{HH}|2|S_{VV}|\cos(\phi_{HH} - \phi_{VV}) + \\ + 4|S_{HH}||S_{HV}|\sin(\phi_{HH} - \phi_{HV}) - 4|S_{VV}||S_{HV}|\sin(\phi_{VV} - \phi_{HV}) \quad (1.2.34)$$

b.2 Amplitude and Partial Phase: Reconstruction of a target scattering matrix does not require accurate or complete phase measurements. Partial phase or crude phase measurements, i.e., determining the lag or lead of one scattering matrix element with respect to the other, as well as necessary amplitude measurements are sufficient.

This method was first considered by Kennaugh (1952) in which he made five amplitude measurements together with two crude phase measurements. It allowed him to reconstruct the scattering matrix with all phases being relative to $[S_{HH}(0)]$. It was attempted here to follow Kennaugh's method and derive the scattering matrix $[S]_{RSM}$ in which the phase of S_{HV} is taken to be the relative phase. The result showed it to be possible to take five amplitude and two crude or partial phase measurements and reconstruct $[S]_{RSM}$, but the mathematics were rather involved; therefore, it was decided to take one more amplitude measurement of $S_{HV}(22.5^\circ)$.

The theory applied to this method is the same as the one applied to the methods of Section 1.2.4b; therefore, only the key steps will be outlined here:

- 1) Measure $|S_{HH}(0)|$, $|S_{HV}(0)|$, and determine which of these leads or lags the other. This will yield the proper sign of phase $(\phi_{HH} - \phi_{HV})$.
- 2) Rotate antenna system by 22.5° and measure $|S_{HV}(22.5^\circ)|$.
- 3) Rotate antenna system by 22.5° further and measure $|S_{HV}(45^\circ)|$ and $|S_{VV}(45^\circ)|$. Note that if $|S_{HH}(45^\circ)|$ is measured instead of $|S_{VV}(45^\circ)|$, there will be a sign difference in the resulting set of two equations containing the two unknown phases $(\phi_{HH} - \phi_{HV})$ and $(\phi_{VV} - \phi_{HV})$.
- 4) The antenna system is rotated 45° more to obtain $|S_{VV}|$, $|S_{HV}(90^\circ)|$, and the lag or lead of one with respect to the other. Note that measurement of $|S_{VV}|$ is not necessary because $|S_{VV}|$, $|S_{HV}(90^\circ)| = |S_{HH}(0^\circ)|$.
- 5) Since all magnitudes will be measured, the unknown phases can be solved for and they will be given in (1.2.30) and (1.2.31) with sign ambiguity. But since in steps 1) and 4) the proper signs of these phases have been measured, the sign ambiguities can be resolved.

This completes the measurement of target scattering matrices using linearly polarized receive-transmit antenna systems and partial phase measuring equipment.

b.3 Measurement of Scattering Matrix in Mixed Polarization Bases

(Amplitude-Only): In Section 1.2.4b a method utilizing seven amplitude measurements to recover the scattering matrix was presented. Measurements taken were in a single polarization basis, namely the transmit-receive antenna system was either linearly or circularly polarized.

Using the mixed basis system will not reduce the number of measurements from the number taken by using a single polarization basis system. Seven amplitude measurements will be necessary to determine the scattering matrix completely. This method was considered by Ross and Freeney (1964), but since only their final results were available to us, the theory and derivations presented in (Beker and Boerner, 1983) need not be the same as those of Ross and Freeney (1964).

Proceeding with the following amplitude measurements, the relative phase scattering matrix $[S]_{\text{RSM}}$ will be determined:

- Transmit vertical polarization and receive vertical and horizontal simultaneously to obtain $|S_{VV}|$ and $|S_{HV}|$.
- If $|S_{HV}| \neq 0$, rotate a linearly polarized receiving antenna by 45° and transmit with vertical antenna to measure $|S_{45^\circ, V}|$; also use a right circularly polarized antenna to obtain $|S_{RC, V}|$.
- Rotate the transmitting antenna (if horizontally polarized transmitting antenna is unavailable) by 90° and receive horizontal, right circular, and linear 45° to measure $|S_{HH}|$, $|S_{RC, H}|$, $|S_{45^\circ, H}|$.

Step b) yields phase $(\phi_{HV} - \phi_{VV})$

$$2|S_{45^\circ, V}|^2 = |S_{HV}|^2 + |S_{VV}|^2 + 2|S_{HV}||S_{VV}|\cos(\phi_{HV} - \phi_{VV}). \quad (1.2.34)$$

$$2|S_{RC, V}|^2 = |S_{HV}|^2 + |S_{VV}|^2 - 2|S_{HV}||S_{VV}|\sin(\phi_{HV} - \phi_{VV}). \quad (1.2.35)$$

Whereas, step c) yields phase $(\phi_{HV} - \phi_{HH})$ and magnitude $|S_{HH}|$

$$2|S_{45^\circ, H}|^2 = |S_{HH}|^2 + |S_{HV}|^2 + 2|S_{HV}||S_{HH}|\cos(\phi_{HV} - \phi_{HH}) \quad (1.2.36)$$

$$2|S_{RC, H}|^2 = |S_{HH}|^2 + |S_{HV}|^2 - 2|S_{HV}||S_{HH}|\sin(\phi_{HV} - \phi_{HH}) \quad (1.2.37)$$

Equations (1.2.34) and (1.2.36) determine the relative phases $(\phi_{HV} - \phi_{VV})$ and $(\phi_{HV} - \phi_{HH})$, respectively, but both contain sign ambiguities that can be resolved by (1.2.35) and (1.2.37) since only one value of $(\phi_{HV} - \phi_{VV})$ and $(\phi_{HV} - \phi_{HH})$ of each satisfies these two equations. Therefore $[S]_{\text{RSM}}$ can be completely determined.

1.2.4c Concluding Remarks

In discussing several methods of scattering matrix measurements, it was found in (Beker and Boerner, 1983) that measurements should not be made with all measuring antenna polarizations located on one and the same great circle of the Poincaré sphere. As a result, ambiguities were introduced in both

the phases of the scattering matrix elements and the polarization state measurements for the amplitude-only case. Phase differences between scattering matrix elements can only be determined if partial phase or other than amplitude-only measurements along one great circle are made. Similar arguments were shown to apply to polarization state measurements in order to resolve ambiguity in the sense of polarization of an elliptically polarized wave as is deliberated in detail in (Beker and Boerner, 1983).

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1.3 BASIC PRINCIPLES OF RADAR POLARIMETRY: MUELLER MATRIX PRESENTATION

1.3.1 The Scattering Matrix

In general, in radar target detection the scattering matrix relates the vectors representing the scattered and incident fields. In practice, the technique consists of having an electromagnetic radiation originating from a radar transmitter, scattered by the object under detection and sampled by a radar receiver.

The scattering matrix is usually defined in terms of arbitrary transmitter-receiver arrangements; therefore, it defines in turns, the scatterer (target) properties. Since the scattering matrix of an object can be determined by measurements, the scattering properties of many complex objects can be studied through the study of their scattering matrix. It has also been shown that a radar target is sensitive to the polarization of the incident field and acts as a polarization transformer and indeed the scattering matrix describes the polarization transformation characteristics of the target (M.Sc. thesis of Saatchi 1983).

The frequency-dependent scattering process provides a linear relation between the polarization of the scattered field and the polarization of the incident field. $\underline{h}^s = [S]\underline{h}^i$, where here $x \neq H, y \neq V$

$$\begin{bmatrix} h_x^s \\ h_y^s \end{bmatrix} = \begin{bmatrix} |S_{xx}|e^{j\phi_{xx}} & |S_{xy}|e^{j\phi_{xy}} \\ |S_{yx}|e^{j\phi_{yx}} & |S_{yy}|e^{j\phi_{yy}} \end{bmatrix} \begin{bmatrix} h_x^i \\ h_y^i \end{bmatrix} \quad (1.3.1a)$$

The values of the four complex components of the scattering matrix depend upon the transmitted and received polarization states, the aspect of the object, and the scattering properties of the object. $[S]_{SMA}$ is the scattering matrix with absolute phase and it can be written as

$$[S]_{SMA} = \begin{bmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{bmatrix} = e^{j\phi_{xy}} \begin{bmatrix} |S_{xx}|e^{j(\phi_{xx}-\phi_{xy})} & |S_{xy}| \\ |S_{yx}|e^{j(\phi_{yx}-\phi_{xy})} & |S_{yy}|e^{j(\phi_{yy}-\phi_{xy})} \end{bmatrix} \quad (1.3.1b)$$

$$[S]_{SMA} = e^{j\phi_{xy}} [S]_{SMR} \quad (SMR: \text{Scattering matrix with relative phase})$$

1.3.2 The Mueller Matrix

The Mueller matrix formulation is based upon the representation of the state of polarization of the electromagnetic wave by a Stokes vector. The representation of the repolarizing effect of the object is shown by a 4x4 Mueller matrix, all of whose elements are real:

$$\underline{g}^s = [M]\underline{g}^i \quad (1.3.2a)$$

$$\begin{bmatrix} g_0^s \\ g_1^s \\ g_2^s \\ g_3^s \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} g_0^i \\ g_1^i \\ g_2^i \\ g_3^i \end{bmatrix} \quad (1.3.2b)$$

The real elements of the Mueller matrix can be found from the scattering matrix which relates the polarization vectors of the incident and scattered fields.

We can also show that the Stokes vector is related to the components of the polarization vector through the relation (R.M.A. Azzam, N.M. Bashara, 1977)

$$\begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -j & j & 0 \end{bmatrix}}_{[A]} \cdot \begin{bmatrix} |h_x|^2 \\ h_x h_y^* \\ h_y h_x^* \\ |h_y|^2 \end{bmatrix} = \begin{bmatrix} |h_x|^2 + |h_y|^2 \\ |h_x|^2 - |h_y|^2 \\ 2\text{Re}(h_x h_y^*) \\ 2\text{Im}(h_x h_y^*) \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad (1.3.3a)$$

$$\underline{g} = [A] \underline{J} \quad (1.3.3b)$$

where \underline{J} is evaluated by direct product of the polarization vector and its Hermitian adjoint. Note that the time average of the vector \underline{J} is also called the coherency vector (Born and Wolf, 1965)

$$\underline{J} = \underline{h}(x,t) \times \underline{h}^*(x,y) \quad (1.3.4)$$

Now, by using the relation between the incident and scattered polarization vectors, the relation between Mueller matrix and scattering matrix is defined as

$$\underline{h}^s = [S] \underline{h}^i$$

$$\underline{h}^s \underline{h}^{s*} = [S] \underline{h}^i [S^*] \underline{h}^{i*} = ([S] \times [S^*]) (\underline{h}^i \times \underline{h}^{i*}) \quad (1.3.5)$$

We know that $\underline{h}^s \underline{h}^{s*} = \underline{J}^s$ and $\underline{h}^i \underline{h}^{i*} = \underline{J}^i$, therefore,

$$\underline{J}^s = [S] \underline{J}^i [S^*] \quad (1.3.6)$$

and substituting the values of \underline{J}^i and \underline{J}^s from (1.3.3b), will give us the relation for the Mueller matrix, where $[S]$ defines the relative phase scattering matrix.

$$[A]^{-1} \underline{g}^s = ([S] \times [S^*]) ([A]^{-1} \underline{g}^i)$$

$$\underline{g}^s = [A] ([S] \times [S^*]) [A]^{-1} \underline{g}^i \quad (1.3.7)$$

or, more concisely

$$[M] = [A]([S] \times [S]^*)[A]^{-1} \quad (1.3.8)$$

The elements of the Mueller matrix with respect to the scattering matrix elements are derived in the M.Sc. thesis of S. Saatchi (June 13, 1983, Appendix B).

1.3.3 Transformation of the Polarization Vector \underline{h} , Scattering Matrix $[S]$, Stokes Vector \underline{g} and Mueller Matrix $[M]$

1.3.3a Transformation of the Polarization Vector

A 2x2 complex polarization vector represents the position of a uniform electric vector in the plane of the wavefront. This representation depends upon the choice of the orthogonal basis.

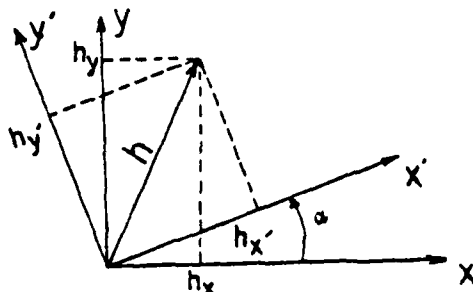


FIGURE 1.4: POLARIZATION VECTOR ROTATION

$$\begin{aligned} h_{x'} &= h_x \cos \alpha + h_y \sin \alpha \\ h_{y'} &= h_x \sin \alpha + h_y \cos \alpha \end{aligned} \quad (1.3.9)$$

Equation (1.3.9) holds when h_x , h_y , $h_{x'}$ and $h_{y'}$ represent the components of the polarization vectors of the instantaneous electric field along the corresponding linear coordinate axis. Equation (1.3.9) can also be written in matrix form as

$$\begin{bmatrix} h_{x'} \\ h_{y'} \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \cdot \begin{bmatrix} h_x \\ h_y \end{bmatrix} \quad (1.3.10)$$

or, more concisely as

$$\underline{h}(x,y) = [R(\alpha)]\underline{h}(x,y) \quad (1.3.11)$$

where the rotation matrix $[R(\alpha)]$ has the following property

$$[R(\alpha)]^{-1} = [R(-\alpha)] \quad (1.3.12)$$

Therefore, we find

$$\underline{h}(x,y) = [R(-\alpha)]\underline{h}(x',y') \quad (1.3.13)$$

The transformation which changes the polarization state of a linear polarization vector (x,y) to a general elliptical basis can be defined (Maffett in, Crispin, and Siegel 1968) as

$$[T] = \begin{bmatrix} e^{j\phi_1} \cos\theta & e^{j\phi_2} \sin\theta \\ -e^{j\phi_3} \sin\theta & e^{j\phi_4} \cos\theta \end{bmatrix} \quad (1.3.14)$$

In order for [T] to be unitary the following condition on the ϕ 's has to be imposed. $\phi_1 + \phi_4 = \phi_2 + \phi_3$, where we can set $\phi_1 = \phi_4 = 0$, $\phi_2 = \xi$ and $\phi_3 = -\xi$, thus, the new form of [T] is

$$[T] = \begin{bmatrix} \cos\theta & -e^{j\xi} \sin\theta \\ e^{-j\xi} \sin\theta & \cos\theta \end{bmatrix} \quad (1.3.15)$$

For the special case of a transformation from the Cartesian to circular basis, we choose $\xi=3\pi/2$ and $\theta=\pi/4$, then

$$[T]_c = 1/\sqrt{2} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \text{ or } \underline{h}(R,L) = [T]_c \underline{h}(x,y) \quad (1.3.16)$$

$$\begin{bmatrix} h_R \\ h_L \end{bmatrix} = 1/\sqrt{2} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \begin{bmatrix} h_x \\ h_y \end{bmatrix} \quad (1.3.17)$$

and each component of the polarization vector in circular basis is found through matrix multiplication of equation (1.3.17).

$$\begin{aligned} h_R &= 1/\sqrt{2}(h_x + jh_y) \\ h_L &= 1/\sqrt{2}(jh_x + h_y) = 1/\sqrt{2}(h_x - jh_y) \end{aligned} \quad (1.3.18)$$

Noteworthy is that in this polarization vector transformation the corresponding wave is traveling along the positive z direction. For a wave traveling along the negative z direction, the vector transformation is

$$\begin{aligned} -h_R &= 1/\sqrt{2}(h_x - jh_y) \\ h_L &= 1/\sqrt{2}(h_x + jh_y) = 1/\sqrt{2}(-jh_x + h_y) \end{aligned} \quad (1.3.19)$$

Equation (1.3.19) results in a transformation matrix $[T']_c$ which is the complex conjugate of the matrix $[T]_c$.

$$[T']_c = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix} \quad (1.3.20)$$

$$[T']_c = [T]_c^* \quad (1.3.21)$$

From equation (1.3.21) we can conclude that if the polarization transformation of an incident wave from (x,y) to (x',y') is represented by $[T]$, the transformation of the scattered wave in the monostatic case is $[T]^*$ (see Kennaugh, 1952)

$$\underline{h}(x',y') = [T]\underline{h}(x,y) \quad (1.3.22)$$

$$\underline{h}_s(x',y') = [T]^*\underline{h}_s(x,y) \quad (1.3.23)$$

By using the transformation matrix from the Cartesian to the circular system, one can show an elliptic vibration given with respect to the Cartesian polarization vector components in a circular polarization basis. Thus, an elliptic vibration of unit amplitude, zero phase, zero azimuth and ellipticity angle τ is given by

$$\underline{h}(x,y) = \begin{bmatrix} h_x \\ h_y \end{bmatrix} = \begin{bmatrix} \cos\tau \\ j\sin\tau \end{bmatrix} \quad (1.3.24)$$

The multiplication of (1.3.24) by $[T]_c$ will give us the same elliptic vibration in a circular basis:

$$\underline{h}(R,L) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \begin{bmatrix} \cos\tau \\ j\sin\tau \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos\tau - \sin\tau \\ j\cos\tau + j\sin\tau \end{bmatrix} \quad (1.3.25)$$

For example, if $\tau = -45^\circ$, equation (1.3.24) gives us a right circular polarization vector, $\underline{h}_R = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -j \end{bmatrix}$ which can be checked by equation (1.3.25) as

$$\underline{h}(R,L) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ (i.e., } h_R)$$

It should also be mentioned that the geometrical parameters θ and ξ in (1.3.15) are the polarization ratio parameters and the matrix can be expressed in terms of the polarization ratio $\rho = \tan\theta e^{j\xi}$ and normalizing $[t]$, it takes on the following form

$$[T] = (1+\rho\rho^*)^{-1/2} \begin{bmatrix} 1 & -\rho \\ \rho^* & 1 \end{bmatrix} \quad (1.3.26)$$

It is known that the transformation matrix [T] may also be defined as a multiplication of two matrices

$$[T] = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} \cos\tau & j\sin\tau \\ j\sin\tau & \cos\tau \end{bmatrix} \quad (1.3.27)$$

which implies the rotation of the coordinate axis and the deformation of the ellipticity or the polarization ellipse (Boerner, 1982). Figure 1.5 shows that the two transformations, (1.3.16) and (1.3.27), are equivalent and describe the same point on the polarization sphere as was shown by Deschamps (1951) and also utilized in the M.Sc. theses of Foo (1982), Saatchi (1983), and Davidovitz (1983).

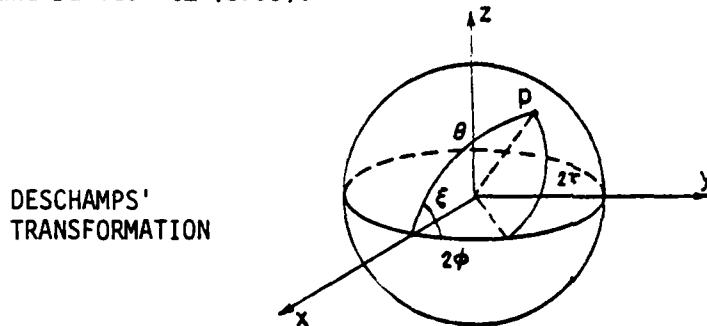


FIGURE 1.5: (G.A. Deschamps, 1951)

1.3.3b Transformation of the Stokes Vector

With the use of the transformation matrix in equation (1.3.26), the polarization vector in the new basis is

$$\underline{h}(x', y') = (1 + \rho\rho^*)^{-1/2} \begin{bmatrix} 1 & -\rho \\ \rho^* & 1 \end{bmatrix} \begin{bmatrix} h_x \\ h_y \end{bmatrix} = (1 + \rho\rho^*)^{-1/2} \begin{bmatrix} h_x - \rho h_y \\ \rho^* h_x + h_y \end{bmatrix} \quad (1.3.28)$$

Substituting $\underline{h}(x', y')$ in equation (1.3.3b), the transformed value of the Stokes vector is found as

$$\underline{g}' = [A] (\underline{h}(x', y') \underline{h}^*(x', y')) \quad (1.3.29)$$

$$\begin{bmatrix} g'_0 \\ g'_1 \\ g'_2 \\ g'_3 \end{bmatrix} = (1 + \rho\rho^*)^{-1} \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -j & j & 0 \end{bmatrix} \begin{bmatrix} (h_x h_x^* - \rho^* h_x h_y^* - \rho h_y h_x^* + \rho\rho^* h_y h_y^*) \\ (\rho h_x h_x^* - h_x h_y^* - \rho^2 h_y h_x^* - \rho h_y h_y^*) \\ (\rho^* h_x h_x^* - \rho^2 h_x h_y^* + h_x h_y - \rho^* h_y h_y^*) \\ (\rho\rho^* h_x h_x^* + \rho^* h_x h_y^* + \rho h_y h_x^* + h_y h_y^*) \end{bmatrix} \quad (1.3.30)$$

where

$$\begin{aligned}
 g'_0 &= (1+\rho\rho^*)^{-1} [h_x h_x^* - \rho^* h_x h_y^* - \rho h_x^* h_y + \rho\rho^* h_y h_y^* + \rho\rho^* h_x h_x^* + \rho^* h_x h_y^* + \rho h_y h_x^* + h_y h_y^*] \\
 &= (1+\rho\rho^*)^{-1} [(1+\rho\rho^*) |h_x|^2 + (1+\rho\rho^*) |h_y|^2] = |h_x|^2 + |h_y|^2 = g_0 \\
 g'_1 &= (1+\rho\rho^*)^{-1} [h_x h_x^* - \rho^* h_x h_y^* - \rho h_x^* h_y + \rho\rho^* h_y h_y^* - \rho\rho^* h_x h_x^* - \rho^* h_x h_y^* - \rho h_y h_x^* - h_y h_y^*] \\
 &= (1+\rho\rho^*)^{-1} [(1-\rho\rho^*) (|h_x|^2 - |h_y|^2) - 2(\rho^* h_x h_y^* + \rho h_y h_x^*)] \\
 g'_2 &= (1+\rho\rho^*)^{-1} [\rho h_x h_x^* + h_x h_y^* - \rho^2 h_y h_x^* - \rho h_y h_y^* + \rho^* h_x h_x^* - \rho^*^2 h_x h_y^* + h_x^* h_y^* - \rho^* h_y h_y^*] \\
 &= (1+\rho\rho^*)^{-1} [(\rho+\rho^*) (|h_x|^2 - |h_y|^2) - (\rho^2 h_y h_x^* - \rho^*^2 h_x h_y^*) + (h_x h_y^* + h_x^* h_y)] \\
 g'_3 &= (1+\rho\rho^*)^{-1} \{j[-\rho h_x h_x^* - h_x h_y^* + \rho^2 h_y h_x^* + \rho h_y h_y^* + \rho^* h_x h_x^* - \rho^*^2 h_x h_y^* + h_x h_y^* - \rho h_y h_y^*]\} \\
 &= (1+\rho\rho^*)^{-1} \{j[(\rho^* - \rho) (|h_x|^2 - |h_y|^2) + (\rho^2 h_y h_x^* - \rho^*^2 h_x h_y^*) - (h_x^* h_y - h_x h_y^*)]\}
 \end{aligned} \tag{1.3.31}$$

For example, the Stokes vector in a circular polarization basis ($\rho = -j$) is given as

$$\begin{aligned}
 g'_0 &= |h_x|^2 + |h_y|^2 = g_0 &= I \\
 g'_1 &= 2\text{Im}(h_x h_y^*) = -g_3 &= V \\
 g'_2 &= 2\text{Re}(h_x h_y^*) = g_2 &= U \\
 g'_3 &= -(|h_x|^2 - |h_y|^2) = -g_1 &= -Q
 \end{aligned} \tag{1.3.32}$$

Therefore, the 4x4 transformation matrix for the Stokes vector from linear to circular polarization basis can be derived from (1.3.32).

$$\begin{bmatrix} g'_0 \\ g'_1 \\ g'_2 \\ g'_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix}, \quad \underline{g}' = [T_s] \underline{g} \tag{1.3.33}$$

Noteworthy that g_0 is always invariant through the transformation because it represents the intensity of the wave.

1.3.3c The Scattering Matrix Transformation

In order to transform the scattering matrix of basis (x,y) into the new basis (x',y'), we substitute the transformed values of the polarization vectors in equation (1.3.1).

$$[T^*] \underline{h}^s = [S][T] \underline{h}^i \quad (1.3.34)$$

$$\underline{h}^s = [T^*]^{-1} [S][T] \underline{h}^i \quad (1.3.35)$$

since $[T^*]^{-1} = [T]^T$, a unitary matrix, we have

$$\underline{h}^s = [T^T][S][T] \underline{h}^i \quad (1.3.36)$$

$$[S(x', y')] = [T^T][S(x, y)][T] \quad (1.3.37)$$

Therefore, the elements of the transformed scattering matrix for the general bistatic case are given by

$$\begin{aligned} S_{x'x'} &= (1+\rho\rho^*)^{-1}(S_{xx}+\rho^*S_{xy}+\rho^*S_{yx}+\rho^{*2}S_{yy}) \\ S_{x'y'} &= (1+\rho\rho^*)^{-1}(-\rho S_{xx}+S_{xy}-\rho\rho^*S_{yx}+\rho^*S_{yy}) \\ S_{y'x'} &= (1+\rho\rho^*)^{-1}(-\rho S_{xx}-\rho\rho^*S_{xy}+S_{yx}+\rho^*S_{yy}) \\ S_{y'y'} &= (1+\rho\rho^*)^{-1}(\rho^2 S_{xx}-\rho S_{xy}-\rho S_{yx}+S_{yy}) \end{aligned} \quad (1.3.38a)$$

In a matrix form, equation (1.3.38a) is shown as

$$\begin{bmatrix} S_{x'x'} \\ S_{x'y'} \\ S_{y'x'} \\ S_{y'y'} \end{bmatrix} = (1+\rho\rho^*)^{-1} \begin{bmatrix} 1 & \rho^* & \rho^* & \rho^{*2} \\ -\rho & 1 & -\rho\rho^* & \rho^* \\ -\rho & -\rho\rho^* & 1 & \rho^* \\ \rho^2 & -\rho & -\rho & 1 \end{bmatrix} \cdot \begin{bmatrix} S_{xx} \\ S_{xy} \\ S_{yx} \\ S_{yy} \end{bmatrix} \quad (1.3.38b)$$

Noteworthy that the determinant and the span of the scattering matrix are invariant through the transformation:

$$\begin{aligned} \det\{S(x', y')\} &\text{ is invariant when } |\det T| = 1, \text{ otherwise} \\ \det\{S(x', y')\} &\text{ is different by a factor of } e^{2j\arg(\det T)} \end{aligned} \quad (1.3.39a)$$

$$\begin{aligned} \text{span}\{S(x, y)\} &= |S_{xx}|^2 + |S_{xy}|^2 + |S_{yx}|^2 + |S_{yy}|^2 \\ &= \text{span}\{S(x', y')\} = |S_{x'x'}|^2 + |S_{x'y'}|^2 + |S_{y'x'}|^2 \\ &\quad + |S_{y'y'}|^2 = \text{invariant} \end{aligned} \quad (1.3.39b)$$

As an example, the scattering matrix in circular polarization basis ($=-j$) is given by

$$\begin{bmatrix} C_{RR} \\ C_{RL} \\ C_{LR} \\ C_{LL} \end{bmatrix} = 1/2 \begin{bmatrix} 1 & j & j & -1 \\ j & 1 & -1 & j \\ j & -1 & 1 & j \\ -1 & j & j & 1 \end{bmatrix} \begin{bmatrix} S_{xx} \\ S_{xy} \\ S_{yx} \\ S_{yy} \end{bmatrix} \quad (1.3.40)$$

or, more concisely as

$$\begin{bmatrix} C_{R,L} \end{bmatrix} = \begin{bmatrix} C_{RR} & C_{RL} \\ C_{LR} & C_{LL} \end{bmatrix} = \begin{bmatrix} (S_{xx}-S_{yy})/2+j(S_{xy}+S_{yx})/2 & (S_{xy}-S_{yx})/2+j(S_{xx}+S_{yy})/2 \\ (S_{yx}-S_{xy})/2+j(S_{xx}+S_{yy})/2 & (S_{yy}-S_{xx})/2+j(S_{xy}+S_{yx})/2 \end{bmatrix} \quad (1.3.41)$$

It should be mentioned that in the monostatic case and for an isotropic propagation space, the reciprocity condition holds. This implies that the scattering matrix in any polarization basis is symmetric ($S_{xy}=S_{yx}$).

$$\begin{bmatrix} C_{R,L} \end{bmatrix} = \begin{bmatrix} (S_{xx}-S_{yy})/2+jS_{xy} & j(S_{xx}+S_{yy})/2 \\ j(S_{xx}+S_{yy})/2 & (S_{yy}-S_{xx})/2+jS_{yx} \end{bmatrix} \quad (1.3.42)$$

1.3.3d The Mueller Matrix Transformation

In equation (1.3.8), we showed that the Mueller matrix is derived from the scattering matrix. Thus, the effect of the polarization transformation will appear in (1.3.8) by substituting the transformed elements of the scattering matrix from (1.3.37) into (1.3.8).

$$\begin{aligned} [S(x',y')] &= [T^T][S(x,y)][T] \\ [M] &= A(SxS^*)A^{-1} \\ [M'] &= A([S(x',y')]x[S^*(x',y')])A^{-1} \end{aligned} \quad (1.3.43)$$

From equation (1.3.38), we have

$$\begin{aligned} S_{x'x'} &= S_{xx}+\rho^*S_{xy}+\rho S_{yx}+\rho^2S_{yy} \\ S_{x'y'} &= -\rho S_{xx}+S_{xy}-\rho\rho^*S_{yx}+\rho^*S_{yy} \\ S_{y'x'} &= -\rho S_{xx}-\rho\rho^*S_{xy}+S_{yx}+\rho^*S_{yy} \\ S_{y'y'} &= \rho^2S_{xx}-\rho S_{xy}-\rho S_{yx}+S_{yy} \end{aligned} \quad (1.3.44)$$

and the complex conjugate values of the transformed scattered matrix elements are as follows

$$\begin{aligned} S_{x'x'}^* &= S_{xx}^*+\rho^*S_{xy}^*+\rho S_{yx}^*+\rho^2S_{yy}^* \\ S_{x'y'}^* &= -\rho^*S_{xx}^*+S_{xy}^*-\rho\rho^*S_{yx}^*+S_{yy}^*+\rho S_{yy}^* \\ S_{y'x'}^* &= -\rho^*S_{xx}^*-\rho\rho^*S_{xy}^*+S_{yx}^*+\rho^*S_{yy}^* \\ S_{y'y'}^* &= \rho^2S_{xx}^*-\rho^*S_{xy}^*-\rho^*S_{yx}^*+S_{yy}^* \end{aligned} \quad (1.3.45)$$

Substituting (1.3.44) and (1.3.45) into (1.3.43), results for the general bistatic case in:

$$m'_{11} = 1/2(|S_{x'x'}|^2 + |S_{x'y'}|^2 + |S_{y'x'}|^2 + |S_{y'y'}|^2) = m_{11} \quad (1.3.46a)$$

$$m'_{12} = 1/2(|S_{x'x'}|^2 - |S_{y'y'}|^2 - |S_{x'y'}|^2 + |S_{y'x'}|^2) \quad (1.3.46b)$$

$$m'_{13} = \text{Re}\{S_{x'x'}S_{x'y'}^*\} + \text{Re}\{S_{y'x'}S_{y'y'}^*\} \quad (1.3.46c)$$

$$m'_{14} = -\text{Im}\{S_{x'x'}^*S_{x'y'}\} - \text{Im}\{S_{y'x'}^*S_{y'y'}\} \quad (1.3.46d)$$

$$m'_{21} = 1/2(|S_{x'x'}|^2 - |S_{y'y'}|^2 + |S_{x'y'}|^2 - |S_{y'x'}|^2) \quad (1.3.47a)$$

$$m'_{22} = 1/2(|S_{x'x'}|^2 + |S_{y'y'}|^2 - |S_{x'y'}|^2 - |S_{y'x'}|^2) \quad (1.3.47b)$$

$$m'_{23} = \text{Re}\{S_{x'x'}S_{x'y'}^*\} - \text{Re}\{S_{y'x'}^*S_{y'y'}\} \quad (1.3.47c)$$

$$m'_{24} = -\text{Im}\{S_{x'x'}^*S_{x'y'}\} + \text{Im}\{S_{y'x'}^*S_{y'y'}\} \quad (1.3.47d)$$

$$m'_{31} = \text{Re}\{S_{x'x'}S_{y'x'}^*\} + \text{Re}\{S_{x'y'}S_{y'y'}^*\} \quad (1.3.48a)$$

$$m'_{32} = \text{Re}\{S_{x'x'}S_{y'x'}^*\} - \text{Re}\{S_{x'y'}S_{y'y'}^*\} \quad (1.3.48b)$$

$$m'_{33} = \text{Re}\{S_{x'x'}S_{y'y'}^*\} + \text{Re}\{S_{x'y'}S_{y'x'}^*\} \quad (1.3.48c)$$

$$m'_{34} = -\text{Im}\{S_{x'x'}^*S_{y'x'}\} - \text{Im}\{S_{x'y'}^*S_{y'x'}\} \quad (1.3.48d)$$

$$m'_{41} = \text{Im}\{S_{x'x'}^*S_{y'x'}\} - \text{Im}\{S_{x'y'}^*S_{y'y'}\} \quad (1.3.49a)$$

$$m'_{42} = \text{Im}\{S_{x'x'}^*S_{y'y'}\} + \text{Im}\{S_{x'y'}^*S_{y'y'}\} \quad (1.3.49b)$$

$$m'_{43} = \text{Im}\{S_{x'x'}^*S_{y'y'}\} + \text{Im}\{S_{x'y'}^*S_{y'x'}\} \quad (1.3.49c)$$

$$m'_{44} = \text{Re}\{S_{x'x'}S_{y'y'}^*\} + \text{Im}\{S_{x'y'}S_{y'x'}^*\} \quad (1.3.49d)$$

which establishes the relationship between $[M]$ and $[S]$, as will be summarized in Table 3 after introducing the modified Mueller matrix and the Graves Power Matrix $[P] = [P_H] + [P_V]$.

1.3.4 The Modified Stokes Reflection Matrix $[M_m]$, for the Monostatic, Reciprocal Case

In radar it is often more useful to use the modified Mueller matrix (Kennaugh, 1949-1954; Huynen 1970) $[M_m]$, which is expressed in terms of the modified Stokes vectors $\underline{g}_m^i, \underline{g}_m^s$, where by definition of (1.3.3a)

$$\underline{g}^s = [M]\underline{g}^i, \underline{g} = (I, Q, U, V) \quad (1.3.50)$$

and with

$$\underline{g}_m = \left(\frac{1}{2}(I + Q), \frac{1}{2}(I - Q), U, V \right) = (I_A, I_B, U, V) \quad (1.3.51)$$

$$g_m = |h_A|^2 = I_A$$

$$g_m^0 = |h_B|^2 = I_B$$

1

(1.3.52)

$$g_{m_2} = 2\text{Re}\{h_A h_B^*\} = U$$

$$g_{m_3} = 2\text{Im}\{h_A h_B^*\} = V$$

(1.3.52 cont.)

We find

$$\underline{g}_m^s(A,B) = [M_m] \underline{g}_m^i(A,B) \quad (1.3.53)$$

The two Mueller matrices $[M]$ and $[M_m]$ are then related using the transformation matrix $[R]$ with

$$\underline{g}_m = [R] \underline{g} [R] = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{2} & -\frac{1}{2} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1.3.54)$$

so that

$$[M_m] = [R][M][R^{-1}] \quad (1.3.55)$$

or

$$[M] = [R^{-1}][M_m][R] \quad (1.3.56)$$

The relationship between $[S], [M], [M_m], [P] = ([P_H] + [P_V])$ and the co/cross-polarization coordinates on the polarization sphere are given in Table 3 after Section 1.3.6.

1.3.5 The Graves Power Matrix $[P] = [P_H] + [P_V]$

For the sake of completeness we are introducing here the definition of the Graves' power matrix $[P]$ (Graves, 1956), and its supplementary power matrices $[P_H]$ and $[P_V]$ which can be determined from amplitude measurements

only as was shown in detail in the M.Sc. thesis of Chan (1981). It will be shown that with knowledge of $[P_H]$ and $[P_V]$ of the target, the associated

$[P]$, $[S]_{SMR}$ and $[M]$ can be completely specified, and vice versa.

1.3.5.a Formulation of the Power Scattering Matrix

When a radar target with scattering matrix $[S]$ is illuminated with an incident wave radiated by a transmitting antenna with polarization \underline{h}^t , its scattered wave polarization is given by

$$\underline{h}^s = [S] \underline{h}^t \quad (1.3.57)$$

$$P_b = \underline{h}^{s*} \cdot \underline{h}^s \quad (1.3.58)$$

Substituting (1.3.47) into (1.3.48) gives

$$P_b = (\underline{h}^t)^T [S]^T [S] \underline{h}^t \quad (1.3.59)$$

Graves (1956) defined the power scattering matrix $[P]$ as

$$P = [S]^T [S] \quad (1.3.60)$$

Therefore, (1.3.40) can be written as

$$P_b = (\underline{h}^t)^T [P] \underline{h}^t \quad (1.3.61)$$

where $[P]$ specifies the total power backscattered from the target for any transmitting polarization.

1.3.5b Properties of the Power Scattering Matrix

In the polarization basis $PB(HV)$, from equation (1.3.60), $[P]$ can be expanded as

$$[P] = [S]^T [S]$$

$$= \begin{bmatrix} S_{HH}^* S_{HH} + S_{HV}^* S_{HV} & S_{HH}^* S_{HV} + S_{HV}^* S_{VV} \\ S_{HH}^* S_{HV} + S_{HV}^* S_{VV} & S_{HV}^* S_{HV} + S_{VV}^* S_{VV} \end{bmatrix} \quad (1.3.62a)$$

$$\text{or} \quad [P] = \begin{bmatrix} |S_{HH}|^2 + |S_{HV}|^2 & (S_{HH}^* S_{HV} + S_{HV}^* S_{VV}) \\ (S_{HH}^* S_{HV} + S_{HV}^* S_{VV}) & |S_{HV}|^2 + |S_{VV}|^2 \end{bmatrix} \quad (1.3.62b)$$

The diagonal elements of $[P]$ are real and the off-diagonal elements form a conjugate pair. Hence, $[P]$ is a Hermitian matrix and such a matrix can always be diagonalized by a similarity transformation of the form

$$[U]^{-1} [P] [U] = [U]^T [P] [U] = [P_d] \quad (1.3.63)$$

where $[P_d]$ is the power scattering matrix in diagonal form with real diagonal elements, the eigenvalues of $[P]$ are real, the eigenvectors are orthogonal and $[U]$ is unitary transformation matrix constructed by the eigenvectors of $[P]$.

Moreover, the same unitary matrix $[U]$ which diagonalizes $[P]$ by a similarity transformation diagonalizes the corresponding scattering matrix $[S]$ by a congruent transformation (Chan, 1981). Furthermore, the eigenvalues of the power scattering matrix are simply the magnitudes squared of the respective eigenvalues of the scattering matrix. If the diagonal scattering matrix is given by

$$[S_d] = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \quad (1.3.64a)$$

then the diagonal power scattering matrix is given by

$$[P_d] = \begin{bmatrix} \lambda_1 \lambda_1^* & 0 \\ 0 & \lambda_2 \lambda_2^* \end{bmatrix} = \begin{bmatrix} |\lambda_1|^2 & 0 \\ 0 & |\lambda_2|^2 \end{bmatrix} = [S_d]^T [S_d] \quad (1.3.64b)$$

In other words, knowledge of $[P]$ provides the information to determine the x-pol nulls (eigenvectors) of the corresponding $[S]$ which specify the polarization to be used for maximum power return. Also, from (1.3.52), the trace of $[P]$ gives

$$\text{Tr}([P]) = |S_{HH}|^2 + |S_{VV}|^2 + |S_{HV}|^2 = \text{span}\{[S]\} = p \quad (1.3.65)$$

However, the co-pol nulls of $[S]$ cannot be determined from $[P]$. It is because we cannot extract the relative phases among the elements in $[S]$ from $[P]$. Therefore, $[P]$ only provides x-pol and p of $[S]$ but not the co-pol nulls. Hence, $[S]$ cannot be reconstructed from the knowledge of $[P]$ alone (Chan 1981) and $[P]$ is not unique.

1.3.6 Decomposition of $[P]$ into two supplementary matrices $[P_H]$ and $[P_V]$

It is desirable to make use of the power scattering matrix concept to obtain information of the backscattered power from the target which leads to the reconstruction of $[S]_{\text{SMR}}$. The reason that we cannot retrieve relative phase information from $[P]$ is that the product $S_{HH}^* S_{HV}$ and $S_{HV}^* S_{VV}$ which carry relative phase information are expressed as sums in $[P]$. If we can find a way to separate the sum as two individual products, then relative phase information can readily be found.

The power scattering matrix $[P]$ describes the total power backscattered from a target, i.e., the sum of the power backscattered in any pair of orthogonal channels, say horizontal (H) and vertical (V) channels. We will define $[P_H]$ and $[P_V]$ as matrices to describe the power backscattered in the horizontal and vertical channels, respectively, where

$$[P] = [P_H] + [P_V] \quad (1.3.66)$$

Substituting (1.3.56) into (1.3.61) gives

$$\begin{aligned} P_b &= (\underline{h}^t)^T ([P_H] + [P_V]) \underline{h}^t \\ &= (\underline{h}^t)^T [P_H] \underline{h}^t + (\underline{h}^t)^T [P_V] \underline{h}^t \\ &= P_{bH} + P_{bV} \end{aligned} \quad (1.3.67a)$$

where P_{bH} and P_{bV} , respectively, are the power backscattered in the horizontal and vertical channels with any transmitting antenna polarization. Hence,

$$P_{bH} = (\underline{h}^t)^T [P_H] \underline{h}^t \quad (1.3.67b)$$

$$P_{bV} = (\underline{h}^t)^T [P_V] \underline{h}^t \quad (1.3.67c)$$

It is shown in (Chan, 1981) that

$$[P_H] = \begin{bmatrix} |S_{HH}|^2 & S_{HH}^* S_{HV} \\ (S_{HH}^* S_{HV})^* & |S_{HV}|^2 \end{bmatrix} \quad (1.3.68a)$$

$$[P_V] = \begin{bmatrix} |S_{HV}|^2 & S_{HV}^* S_{VV} \\ (S_{HV}^* S_{VV})^* & |S_{VV}|^2 \end{bmatrix} \quad (1.3.68b)$$

The measurements of $[P_H]$ and $[P_V]$, as discussed in Chan (1981), involve amplitude measurements only, no phase measurements are necessary. These two matrices provide relative phase information that is essential in the reconstruction of the scattering matrix with relative phase $[S]_{SMR}$ which will be discussed in the following section.

1.3.7 Reconstruction of $[S]_{SMR}$ from $[P_H]$ and $[P_V]$

Unlike $[P]$, both $[P_H]$ and $[P_V]$ provide information about the relative phases of $[S]_{SMR}$, where

$$[S(HV)]_{SMR} = \begin{bmatrix} |S_{HH}| e^{j(\phi_{HH} - \phi_{HV})} & |S_{HV}| \\ |S_{HV}| & |S_{VV}| e^{j(\phi_{VV} - \phi_{HV})} \end{bmatrix} \quad (1.3.69a)$$

It is obvious that $|S_{HH}|$, $|S_{HV}|$ and $|S_{VV}|$ can readily be obtained from $[P_H]$ and $[P_V]$. Now, the relative phase of $|S_{HH}|$ can be obtained from the off-diagonal from the off-diagonal elements of $[P_H]$ in (1.3.68a) as follows:

$$\phi_{HH} - \phi_{HV} = \arg\{S_{HH} S_{HV}^*\} = \arctan \frac{\text{Im}\{S_{HH} S_{HV}^*\}}{\text{Re}\{S_{HH} S_{HV}^*\}} \quad (1.3.70a)$$

Similarly, from the off-diagonal elements of $[P_V]$ in (1.3.68b), the relative phase of $|S_{VV}|$ can be recovered as follows:

$$\phi_{VV} - \phi_{HV} = \arg\{S_{HV}^* S_{VV}\} = \arctan \frac{\text{Im}\{S_{HV}^* S_{VV}\}}{\text{Re}\{S_{HV}^* S_{VV}\}} \quad (1.3.70b)$$

As a result, $[S(HV)]_{SMR}$ can be completely specified by elements of $[P_H]$ and $[P_V]$.

1.3.8 Summary

The existing matrix inter-relating identities are collected in Tables 3 and 4, which should serve as a useful reference table. For more details we refer to the M.Sc. Theses of Chan (1981), Foo (1982), Saatchi (1983), Davidovitz (1983) and Huang (1984).

1.3.9 References

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TABLE 3: RECONSTRUCTION OF $[M]$, $[M_m]$ $[P_V]$, $[P_H]$, $[P_V]$
AND OPTIMAL POLARIZATION FROM $[S]$

$[M]$	$[M_m]$
$m_{11} = 1/2 (S_{AA} ^2 + 2 S_{AB} ^2 + S_{BB} ^2)$ $m_{12} = m_{21} = 1/2 (S_{AA} ^2 - S_{BB} ^2)$ $m_{13} = m_{31} = \text{Re}\{S_{AA}S_{AB}^* + S_{AB}S_{BB}^*\}$ $m_{14} = m_{41} = \text{Im}\{S_{AA}S_{AB}^* + S_{AB}S_{BB}^*\}$ $m_{22} = 1/2 (S_{AA} ^2 - 2 S_{AB} ^2 + S_{BB} ^2)$ $m_{23} = m_{32} = \text{Re}\{S_{AA}S_{AB}^* - S_{AB}S_{BB}^*\}$ $m_{24} = -m_{42} = \text{Im}\{S_{AA}S_{AB}^* - S_{AB}S_{BB}^*\}$ $m_{33} = \text{Re}\{S_{AA}S_{BB}^*\} + S_{AB} ^2$ $m_{34} = -m_{43} = \text{Im}\{S_{AA}S_{BB}^*\}$ $m_{44} = m_{33} + m_{22} - m_{11}$	$M_{11} = S_{AA} ^2$ $M_{12} = S_{AB} ^2 = M_{21}$ $M_{13} = \text{Re}\{S_{AA}S_{AB}^*\} = 1/2 M_{31}$ $M_{14} = \text{Im}\{S_{AA}S_{AB}^*\} = 1/2 M_{41}$ $M_{22} = S_{BB} ^2$ $M_{23} = \text{Re}\{S_{AB}S_{BB}^*\} = 1/2 M_{32}$ $M_{24} = \text{Im}\{S_{AB}S_{BB}^*\} = -1/2 M_{42}$ $M_{33} = \text{Re}\{S_{AA}S_{BB}^*\} + S_{AB} ^2$ $M_{34} = \text{Im}\{S_{AA}S_{BB}^*\} = -M_{43}$ $M_{44} = M_{33} - 2M_{12}$
$[P] = [P_H] + [P_V]$	CO-POL & X-POL Nulls
$[P] = \begin{bmatrix} a & c \\ c^* & b \end{bmatrix}$ $a = S_{HH} ^2 + S_{HV} ^2$ $b = S_{HV} ^2 + S_{VV} ^2$ $c = S_{HH}^*S_{HV} + S_{HV}^*S_{VV}$ $[P_H] = \begin{bmatrix} a_H & c_H \\ c_H^* & b_H \end{bmatrix}$ $a_H = S_{HH} ^2$ $b_H = S_{HV} ^2$ $c_H = S_{HH}^*S_{HV}$ $[P_V] = \begin{bmatrix} a_V & c_V \\ c_V^* & b_V \end{bmatrix}$ $a_V = S_{HV} ^2$ $b_V = S_{VV} ^2$ $c_V = S_{HV}^*S_{VV}$	<p>COLATITUDE: $\theta = \cos^{-1} = \frac{ u ^2 - 1}{ u ^2 + 1}$</p> <p>LONGITUDE: $\phi' = -\tan^{-1} = \frac{\text{Im}(u)}{\text{Re}(u)}$</p> <p>where $u = \frac{1 - j\rho}{1 + j\rho}$,</p> <p>and $\rho = \frac{B^2 \pm \sqrt{B^2 - 4AC}}{2A}$</p> <p><u>CO-POL Nulls</u> $A = S_{BB}$ $B = 2S_{AB}$, $C = S_{AA}$</p> <p><u>X-POL Nulls</u> $A = S_{BB}S_{AB}^* + S_{AA}^*S_{AB} = -C^*$ $B = S_{AA} ^2 - S_{BB} ^2$</p>

TABLE 4: RECONSTRUCTION OF $[S]_{SMR}$ FROM $[M]$, $[M_m]$ and OPTIMAL POLARIZATIONS

elements of $[S]_{SMR}$	from $[M]$	from $[M_m]$	from $[P_A]$ and $[P_V]$ (A=H, B=V)
$ S_{AA} $	$\sqrt{1/2(m_{11} + 2m_{12} + m_{22})}$	$\sqrt{M_{11}}$	$\sqrt{a_A}$
$ S_{AB} = S_{BA} $	$\sqrt{1/2(m_{11} - m_{22})}$	$\sqrt{M_{12}}$	$\sqrt{b_A} = \sqrt{a_B}$
$ S_{BB} $	$\sqrt{1/2(m_{11} - 2m_{12} - m_{22})}$	$\sqrt{M_{22}}$	$\sqrt{b_B}$
$\phi_{AA} - \phi_{AB}$	$\tan^{-1} \left\{ \frac{m_{14} + m_{24}}{m_{13} + m_{23}} \right\}$	$\tan^{-1} \left\{ M_{14}/M_{13} \right\}$	$\tan^{-1} \left\{ \frac{\text{Im } C_A}{\text{Re } C_A} \right\}$
$\phi_{BB} - \phi_{AB}$	$\tan^{-1} \left\{ \frac{m_{41} - m_{42}}{m_{31} - m_{32}} \right\}$	$\tan^{-1} \left\{ M_{42}/M_{32} \right\}$	$\tan^{-1} \left\{ \frac{\text{Im } C_B}{\text{Re } C_B} \right\}$
<p><u>From optimal polarizations</u></p> <p>$[S(A,B)] = K \begin{bmatrix} x & z \\ z & y \end{bmatrix}$</p> <p>$K = \sqrt{\frac{P}{2}} \{ \rho_1^{CO} + \rho_2^{CO} ^2 + 2 \rho_1^{CO} \rho_2^{CO} ^2 + 2 \}^{-1/2}$</p> <p>$x = -2\rho_1^{CO} \rho_2^{CO} \exp\{-j\phi_E\}$ $\phi_E = \text{phase}(\rho_1^{CO} + \rho_2^{CO})$</p> <p>$y = -2 \exp\{-j\phi_E\}$</p> <p>$z = \rho_1^{CO} + \rho_2^{CO}$</p> <p><u>One Co-Pol and one X-Pol Null are known:</u></p> <p>$K = \sqrt{P/D}$, $D = 2 (\rho^X)^* (\rho^{CO})^2 + \rho^X ^2 + \rho^{CO} ^2(\rho^{CO} - \rho^{CO} \rho^X ^2 - 2\rho^X ^2)$</p> <p>$+ 2\rho^{CO}(\rho^X)^* - \rho^X ^2 + 1 ^2$</p> <p>$x = \rho^{CO}[\rho^{CO} - \rho^{CO} \rho^X ^2 - 2\rho^X] \exp(-j\phi_E)$, $\phi_E = \text{phase}(\rho^X)^*(\rho^{CO})^2 + \rho^X$</p> <p>$y = -[2\rho^{CO}(\rho^X)^* - \rho^X ^2 + 1] \exp(-j\phi_E)$</p> <p>$z = (\rho^X)^*(\rho^{CO})^2 + \rho^X$</p>			

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I.4 RELATIONSHIPS BETWEEN VECTOR SCATTERING THEORY AND POLARIZATION SCATTERING MATRIX CHARACTERISTICS

Based on Bennett's time-domain first order correction to the Physical Optics current approximation, a relationship between the linear monostatic scattering matrix elements and the specular point geometry (electrical principal curvatures) of a radar scatterer is established. The resulting relations are then applied to Huynen's Mueller matrix parameters derived from Kennaugh's radar target polarization characteristic operator theory. Using complex experimental scattering matrix data for perfectly conducting prolate/oblate spheroids, ellipsoids and sphere/cone-capped truncated cylinders obtained on the compact measurement range of the ElectroScience Laboratory, the Ohio State University, the usefulness of these results is established and verified.

1.4.1 First Order Polarization Correction

For the case of a perfectly conducting scatterer, the H-field boundary condition may be used to yield a vector integral equation [1.4.1]

$$\vec{J}(\vec{r}, t) = 2\hat{a}_n \times H_1(\vec{r}, t) + \frac{1}{2\pi} \iint_S \hat{a}_n \times (L\vec{J}(\vec{r}', \tau) \times \hat{a}_R) ds' \quad (1.4.1)$$

where $\vec{J}(\vec{r}, t)$ is the induced surface current density, \vec{r} is the position vector to the observation point, \vec{r}' is that to an integration point, $R = R\hat{a}_R = \vec{r} - \vec{r}'$, and \hat{a}_n is the unit normal to the surface at the observation point. The operator L is defined as

$$L = \frac{1}{R^2} + \frac{1}{RV_0} \frac{\partial}{\partial \tau}$$

with the retarded time $\tau = t - R/V_0$, V_0 being the free space velocity of an electromagnetic wave.

The first term on the right hand side of (1.4.1) is the source term and, if applied to the illuminated region, is identified as the physical optics approximation; whereas the integral term represents the contribution of retarded currents at points on the surface other than the specular point. In the shadow region, physical optics currents are approximated as zero. However, in the neighborhood S_e of the specular point and considering only the contribution of S_e , we find

$$\vec{J}(\vec{r}, t) = \vec{J}_{po}(\vec{r}, t) + \vec{J}_e(\vec{r}, t), \quad \text{with}$$

$$\vec{J}_e(\vec{r}, t) = \frac{1}{2\pi} \iint_{S_e} \hat{a}_n \times (L\vec{J}(\vec{r}', \tau) \times \hat{a}_R) ds' \quad (1.4.2)$$

being the correction to the physical optics current \vec{J}_{po} . The physical optics approximation for the scattered far field impulse response was found to be (Kennaugh and Cosgriff, 1958; Barabenenkov, 1963; Kennaugh and Moffatt, 1956)

$$r_0 \vec{H}_{s(po)}(\vec{r}, t) = \frac{1}{2\pi} \frac{\partial^2}{\partial t^2} A(t) \hat{a}_H \quad (1.4.3)$$

where \hat{a}_{H_i} is the unit vector in the direction of \vec{H}_i , and $A(t)$ is the silhouette area of the scatterer as delineated by the incident impulsive plane wavefront moving at a velocity of $V_0/2$, and r_0 is the radar range. Equation (1.4.3) is known as the Kennaugh-Cosgriff formula. Since the impulse response in (1.4.3) depends solely on the area function, it manifests no depolarization effects. Depolarization effects were taken care of by Bennett, et al (1973) and Bennett (1981) by integrating over S_e in (1.4.2). The correction current \vec{J}_e thus excludes contributions of retarded currents outside S_e . Under this leading edge simplification, the correction obtained is more valid towards the higher frequency end of the phasor frequency response. By ignoring higher order terms in the vector expansion of (1.4.2), a first correction to (1.4.3) is (Bennett et al 1973)

$$r_0 \vec{H}_s(\text{pol}) (\vec{r}, t) = \frac{K_u - K_v}{4\pi} \frac{\partial A}{\partial t} \{ \hat{a}_u H_{ui} - \hat{a}_v H_{vi} \} \quad (1.4.4)$$

where H_{ui} and H_{vi} are the components of the impulse \vec{H}_i in the \hat{a}_u and \hat{a}_v directions respectively at the specular point, i.e. along directions of the principal curvatures K_u and K_v . The first order correction exhibits depolarization effects, which are proportional to the difference in the principal curvatures at the specular point, and take the functional form of the first derivative of the silhouette area.

From (1.4.3) and (1.4.4), the corrected scattered field is thus

$$r_0 \vec{H}_s(\vec{r}, t) = \frac{1}{2\pi} \frac{\partial^2}{\partial t^2} A(t) \hat{a}_{H_i} + \frac{K_u - K_v}{4\pi} \frac{\partial}{\partial t} A(t) \{ (\hat{a}_{H_i} \cdot \hat{a}_u) \hat{a}_u - (\hat{a}_{H_i} \cdot \hat{a}_v) \hat{a}_v \} \quad (1.4.5)$$

with the restriction of a smooth, conducting, convex scatterer assumed in (Bennett et al, 1973).

1.4.2 Scattering Matrix

Since a target behaves as a polarization transformer, complete polarization-depolarization information is required for scattering description. The scattering matrix relates the polarization of the scattered wave to that of the incident wave for a fixed frequency and for a fixed aspect. For instance, in linear horizontal and vertical polarizations,

$$\begin{bmatrix} E_h^s \\ E_v^s \end{bmatrix} = \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix} \quad \text{or} \quad \vec{E}^s = [S] \vec{E}^i \quad (1.4.6)$$

where \vec{E}^i , \vec{E}^s denote the incident and scattered waves, respectively. The elements of $[S]$ are generally complex, and $S_{hv} = S_{vh}$ in the monostatic backscattered case due to reciprocity. It is equally possible to express (1.4.6) in other polarization bases through unitary transformations (See Section 1.3).

To apply polarization correction shown by (1.4.4) and (1.4.5) to radar polarimetry, (1.4.5) is Fourier-transformed to the frequency domain in order to be related to the linear [S], thus giving (Foo, Chaudhuri, Boerner, 1984)

$$\begin{aligned} S_{hh} &= \frac{1}{2\pi} (jk)^2 A(k) + j(jk)^2 A(k) \frac{K_u - K_v}{k4\pi} \cos 2\alpha \\ S_{vv} &= \frac{1}{2\pi} (jk)^2 A(k) - j(jk)^2 A(k) \frac{K_u - K_v}{k4\pi} \cos 2\alpha \\ S_{hv} &= -j(jk)^2 A(k) \frac{K_u - K_v}{k4\pi} \sin 2\alpha = S_{vh} \end{aligned} \quad (1.4.7)$$

where $A(k)$ is the Fourier transform of the silhouette area, and α is the angle between the vertical direction and the direction associated with K_u . Equation (1.4.7) reveals that for smooth targets, under high frequency illumination and to first order approximation, the scattering matrix elements depend on the principal curvature difference at the specular point, which provides an important parameter in target profile reconstruction via differential geometry (Chaudhuri and Boerner; Borden, 1983).

Another application of the above polarization correction is to express the target descriptors in the Mueller matrix in terms of curvature through (1.4.7).

1.4.3 Important target descriptors

It has been shown by Kennaugh that there are special sets of optimal polarization vectors which can nullify either diagonal or the off-diagonal elements of [S] in the general elliptical polarization. The former are called "co-pol nulls" and the latter are "cross-pol nulls", which are uniquely related to the target, and which constitute Kennaugh's target characteristic operator known as the polarization fork on the Poincaré sphere. A knowledge of either both co-pol nulls or one co-pol and one cross-pol is adequate to completely specify the scattering matrix of the target for one aspect and at one frequency. Another way to specify the scattering matrix is in terms of geometrical target parameters. Huynen [9] introduced the Pauli spin matrices and investigated certain eigenvalue problems of [S]. [S] may be expressed as

$$[S] = [U^*(\psi, \tau_m, \nu)]_m \begin{bmatrix} 1 & 0 \\ 0 & \tan^2 \delta \end{bmatrix} [U^*(\psi, \tau_m, \nu)] \quad (1.4.8)$$

where [U] is the set of certain orthonormal vectors derived from [S], m represents the maximum total backscattered power, (ψ, τ, ν) are Eulerian rotation angles about the axes of the Poincaré sphere, ψ is the target orientation angle, and τ is an indicator for target non-symmetry; ν gives the phase difference between the terms of the diagonalized scattering matrix, and has been shown (Manson, Foo, Agrawal, Boerner, 1983) to relate to the principal curvatures of smooth, convex targets. The angle δ determines the spacing between the target's characteristic co-pol nulls of the polarization fork. It is these descriptors which comprise the elements of the Mueller matrix in Huynen's formulation.

1.4.4 Huynen's descriptors in the Mueller's matrix

Given the polarization vectors $\vec{g}(a)$ and $\vec{g}(b)$ for the transmit and receiver antennas, the receiver power P was written as (Huynen 1970)

$$P = [M_\psi] \vec{g}(a) \cdot \vec{h}(b) \quad (1.4.9)$$

where $\vec{g}(a)$ and $\vec{h}(b)$ denote the Stokes vector, respectively, and the Mueller matrix $[M_\psi]$ is

$$[M_\psi] = \begin{bmatrix} A_0 + B_0 & F & C_\psi & H_\psi \\ F & -A_0 + B_0 & G_\psi & D_\psi \\ C_\psi & G_\psi & A_0 + B_\psi & E \\ H_\psi & D_\psi & E_\psi & A_0 - B_\psi \end{bmatrix} ,$$

in which the descriptors are functions of $(\psi, \tau_m, \nu, m, \lambda)$ given in (Huynen, 1970). The sum $A_0 + B_0$ may be considered roughly as a measure of total power in the returned wave from the target. A_0 is associated with regular, smooth, convex type of surface scattering, which contributes to specular returns such as from a sphere. B_0 may be considered as a measure of all the target's non-symmetric, irregular, rough-edged, non-convex depolarizing components of scattering. F is an indicator for target helicity and is orientation independent. C and D are associated with depolarization components of symmetric targets, E and F with depolarization due to non-symmetry. H is coupling due to target orientation and G couples the symmetric and asymmetric aspects of the target (Huynen, 1970, 1982, 1983).

By expressing these descriptors in terms of the elements of the linear $[S]$ and by substituting (1.4.7) for the elements, we obtain

$$A_0 = \frac{1}{8} \frac{k^4}{\pi^2} |A(k)|^2 \quad (1.4.10)$$

$$B_0 = \frac{1}{8} \frac{k^2}{\pi^2} |A(k)|^2 \left(\frac{K_u - K_v}{2} \right)^2 \quad (1.4.11)$$

$$B_\psi = \frac{1}{8} \frac{k^4}{\pi^2} |A(k)|^2 \left(\frac{K_u - K_v}{2k} \right) \cos 4\alpha \quad (1.4.12)$$

$$C_\psi \rightarrow 0 \quad \text{with increasing frequency} \quad (1.4.13)$$

$$D_\psi = \frac{-k^4}{4\pi^2} |A(k)|^2 \left(\frac{K_u - K_v}{2k} \right) \cos 2\alpha \quad (1.4.14)$$

$$F \rightarrow 0 \quad \text{with increasing frequency} \quad (1.4.15)$$

$$E_{\psi} = \frac{k^2}{8\pi^2} |A(k)|^2 \left(\frac{K_u - K_v}{2} \right)^2 \sin 4\alpha \quad (1.4.16)$$

$$H_{\psi} \rightarrow 0 \quad \text{with increasing frequency} \quad (1.4.17)$$

$$G_{\psi} = \frac{k^4}{4\pi^2} |A(k)|^2 \left(\frac{K_u - K_v}{2k} \right) \sin 2\alpha \quad (1.4.18)$$

Since (1.4.7) is derived on the crude assumptions of leading edge (high frequency) and first order effects, smooth, convex, sphere-like targets, (1.4.-10) is a rough approximation and inherits the same severe restrictions. It is interesting to note that even under approximation, A_0 and B_0 show no dependence on target orientation, as they should, whereas the polarization angle α defined earlier renders B_{ψ} , for instance, orientation-dependent.

Moreover, the orientation invariance of $B_{\psi}^2 + E_{\psi}^2$ and $D_{\psi}^2 + G_{\psi}^2$ are also separately satisfied as required in (Huynen, 1970, 1982 and 1983) and discussed in more detail in Manson, Foo, Agrawal, Boerner, (1983). The results of applying the first order physical optics polarization correction to radar polarimetry are established and experimentally verified.

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1.5 THE TARGET COMPLEX NATURAL RESONANCES

The singularity expansion method (SEM) is used to study the characteristic properties (e.g. estimates on material properties and shapes) of the scatterer.

We review the various fields where SEM and its counterparts are used to study such diverse effects as defects in solids (acoustics), interaction of elementary particles (Regge-pole theory) and radar target identification in electromagnetic scattering.

We conclude the review with an analysis of the polarization dependence on SEM: we specifically look at a plane-wave impinging on a thin wire, studying the polarization sensitivity of the residues associated with the eigen resonances.

1.5.1 Introduction

When an electromagnetic wave falls on a perfectly conducting object, currents are set up on the conductor which exhibit shape and surface structure-dependent resonance features. The conductor reradiates at certain characteristic frequencies that are dependent on the resonant properties of the scatterer. One can make estimates on the shape, size, and material properties of the scatterer, provided the resonant frequencies can be extracted from the reradiated fields.

The singularity expansion method (SEM) can be utilized to determine the resonant frequencies by expanding the current distribution in a series in which those resonant frequencies appear as simple poles. This idea goes back to the studies of Rayleigh in acoustics introducing the concept of resonant frequency description. The SEM concept is also utilized in high energy particle physics, there being identified with the Regge-pole theory. The S-matrix approach of Chew, (1966) and Low, () also exploits the resonance feature of the scattering cross-section. The pole-particle, the branch-point threshold and the analytic continuation of unitarity of the S-matrix provide a basis for dynamics. Scattering from elastic and penetrable media is studied in terms of the eigenfrequency expansion method to detect cracks in structures, which is a tensorial problem in general (Langenberg, 1984).

In this study, we are analyzing the polarimetric properties of the residues associated with the particular eigenfrequencies for the electromagnetic vector case which has immediate consequences also on the acousto-elastic case for which a polarization-state description can also be applied. (Sabatier, 1984).

1.5.2 Mathematical Formulation of the Singularity Expansion Method (SEM)

The singularity expansion techniques for solving boundary value problems go back to the works of Rayleigh (1945) in acoustics. The forced oscillations and the consequent radiation from a perfectly conducting sphere and spheroid were looked into by Page and Adams (1938 and 1940).

Rayleigh considered the acoustic field inside a cavity with hard walls (Fig. 1.6)

$$(\nabla^2 - kn^2)\psi = 0 \quad \text{in } V \quad (1.5.1)$$

$$\partial_n \psi = 0 \quad \text{on } \partial V \quad (1.5.2)$$

and $k = \frac{is}{c}$, c is the velocity of acoustic waves in V .

The eigenvalues s_n are pure imaginary and the set $\{\psi_n\}$ forms a complete set.

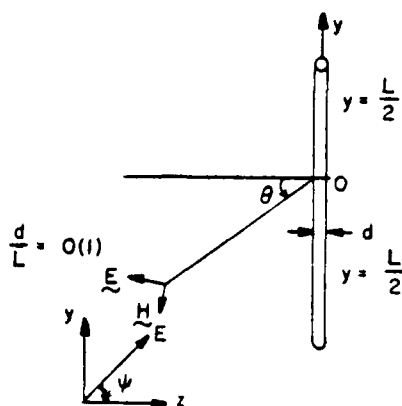


FIGURE 1.6 VECTOR SEM FOR A THIN WIRE SINGLE SCATTERER

We consider the case of V with a compact support. Complete analytical solutions of scattering and radiation are restricted to a few canonical shapes. The fields inside V are expanded using the complete set $\{\psi_n\}$. We find that two types of singularities arise:

- a) singularity of the source, and
- b) singularity (simple poles) at the resonant frequencies of the cavity (Marin 1974a).

The poles on the imaginary axis in the complex s -plane are representation-dependent and are not intrinsic to the scatterer. We refer to these as the interior resonant frequencies.

The other set of poles is off the imaginary axis and to the left half of the s -plane. These are representation independent. We shall be interested in these poles only. These poles are the complex eigenvalues of the homogeneous boundary value problem (equations (1.5.1) and (1.5.2)).

The SEM is found to be an efficient technique for calculating broadband frequency response characteristics from the Laplace Transform relation in time domain (Baum 1976). The transient responses of complex scatterers are dominated by a few sinusoids corresponding to a pole or a pair of poles in the complex s -plane. The target has a large response at such frequencies.

The formulation of the SEM in electromagnetic theory (Dolph and Cho 1980; Ramm 1980a) proceeds as follows:

- i) Take the Laplace Transform of Maxwell's equations. This reduces the initial boundary value problem to a boundary value problem.
- ii) The scattered field is expressed in integral form using the appropriate boundary conditions.

Consider the initial boundary value problem:

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \psi(\vec{r}, t) = 0 \quad (1.5.3)$$

where $\tilde{r} \in V$, $t > 0$.

$$\left. \begin{aligned} \phi(\tilde{r},) &= 0 \\ \phi_t(\tilde{r},0) &= f(\tilde{r}), f \in C_0^\infty \end{aligned} \right\} \quad (1.5.4)$$

and $\phi(\tilde{r}_0, t) = 0$, $\tilde{r}_0 \in \partial V$, $t > 0$

By taking the Laplace Transform we have:

$$\left[\nabla^2 - \left(\frac{s}{c} \right)^2 \right] \tilde{\phi}(\tilde{r}) = 0, \quad \tilde{r} \in V$$

$$\tilde{\phi}(\tilde{r}_0) = 0, \quad \tilde{r}_0 \in \partial V \quad (1.5.5)$$

and a radiation condition for the scattered field.

Let G be the Green's function of equation (1.5.5)

$$(-\nabla^2 + p^2)G = \delta(\tilde{r}-\tilde{r}') \text{ in } V,$$

$$G = 0 \text{ on } \partial V, \quad \text{Re } p > 0 \quad (1.5.6)$$

then the solution of (1.5.3) is

$$\psi = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \exp(pt) \tilde{\Psi}(\tilde{r},s) dp, \quad (1.5.7)$$

where

$$\tilde{\Psi}(\tilde{r},s) = \int_V G(\tilde{r},\tilde{r}', -s^2) f(\tilde{r}') d\tilde{r}' \quad (1.5.8)$$

It can be shown (Lax and Phillips 1971; Ramm 1970) that the contour in (1.5.7) may be moved to the left to get

$$\tilde{\Psi} = \sum_{i,j=1}^{N,M} c_i^{(j)} \frac{t^{j-1}}{(j-1)!} e^{s_i t} + O\left(e^{-|\text{Res}_N t|}\right) \quad (1.5.9)$$

where s_j are the poles of G , and M is the multiplicity of the pole s_j .

In more formal works, one considers the magnetic field given by the integral of the surface current density:

$$(\tilde{I} - 2L) \circ \tilde{J} = \tilde{J} - 2 \int_{\partial V} \hat{n} \times (\nabla' G \times \tilde{J}') ds' = 2\hat{n}_0 \tilde{H}^{\text{inc}} \quad (1.5.10)$$

where \hat{n} , \hat{n}' are unit normal to ∂V into region V .

I = identity operator

L = integral operator

$$= \int_{\partial V} \hat{n} \times (\nabla \times \mathcal{J}) ds$$

$$\mathcal{J}^{inc} = \hat{n} \times \mathcal{H}^{inc}$$

$$G = \frac{e^{-sR}}{4\pi R} = \text{free Green's function}$$

$$R = |\vec{r}_0 - \vec{r}'_0|$$

The integral equation

$$(\tilde{I} - 4\tilde{L}) \circ \mathcal{J} = 2(\tilde{I} + 2\tilde{L}) \circ (\hat{n}_0 \times \mathcal{H}^{inc}) \quad (1.5.11)$$

is of the Fredholm type.

It can be shown that the operators $\tilde{I}-2\tilde{L}$, $\tilde{I}+2\tilde{L}$ have inverses for the same values of s . (Marin 1974b).

The inverse of $(\tilde{I}-2\tilde{L})$ has a pole at $s = s_n$, whenever the equation (1.5.10) has a non-trivial solution at $s = s_n$ (Baum 1976; Baum 1971; Dolph and Cho 1980).

The method of moments replaces the homogeneous integral equation by a matrix equation and the zeros of the kernel matrix are the poles s_n we seek. Rigorous justification of this heuristic procedure has not been established in the literature (Dolph and Cho 1980; Ramm 1980a; Sabatier, 1983/4).

1.5.3 Application of SEM to Target Identification

The poles s_n are dependent on the geometry of the scattering body. Once the relation between these complex poles and the radar pulse signature is established, radar target classification may be possible.

One can look at the poles in the frequency or the time domains, each forming a transform pair with the other. The problem is to find the pole-set for any input signal and compare this set with the library of poles of known targets (Lax and Phillips 1971), assuming that all poles are simple poles, which was recently put in question in (Sabatier, 1983/84).

Also, measuring the time-response of the far-field due to the transient wave, one can establish the size of the target.

1.5.4 Location of the Poles, s_n

It is, in general, very difficult to locate the complex poles of the Green's function. It was proven by Peter Lax, et.al. (1971) that for the Dirichlet Boundary Conditions, the following inequality holds:

$$\text{Im}\{s_n\} < a + b \ln|s_n|, \quad b > 0.$$

In general, the poles s_n of the Green's function coincide with the numbers k_n for which $I + A(k)$ is not invertible.

We have to evaluate the poles numerically. The poles and residues are obtained from an electromagnetic system directly from its impulse response data. We write the impulse response as a sum of exponentially damped sinusoids, that is

$$I(t) = \sum_{r=1}^N A_i e^{s_i t} \quad (1.5.12)$$

with s_i as the poles, and A_i as the residue at pole s_i .

Since we usually deal with a discrete set, we have:

$$I(t) = I_n = \sum_{r=1}^N A_i e^{ns_i \Delta t} \quad (1.5.13)$$

with $n = 0, 1, \dots, 2N-1$.

This non-linear set of equations may be solved using Prony's method ().

The second technique consists of extracting poles using the Cauchy integral in the complex frequency plane.

Consider the integral $\oint_C f(z)dz$, where C is a closed region in the z -plane.

Divide C into N^2 rectangular regions C_1, C_2, \dots, C_N^2 . If the integral around any mesh $C_i = 0$, there are no poles inside the mesh. If, however, the integral around $C_i \neq 0$, there must be at least one pole inside C_i . This technique is basically a moment method and the convergence is slow.

A third technique is essentially the same as above, but uses a certain conjugate operator that reduces the cpu time. This technique uses a set of eigenfunctions of an Hermitian iterated operator which, before the iteration, gives the tangential electric field on the surface due to the surface current. The characteristic equation can be reduced to that of an uniterated real operator when reciprocity holds. Even when the body does not radiate, the technique is found to give good computational accuracy (Inagaki 1978).

Finally, pole tracking by a parameter variation is also found useful (Wilton and Poglozeliski, 1975). We need singularities of an operator L^{-1} , where the operator L appears in equations of the form

$$Lf = g. \quad (1.5.14)$$

We could introduce a parameter α in L , f and g . The parameter α may be the polarization angle of the incident field.

Consider the homogeneous equation

$$Lf = 0 \quad (1.5.15)$$

Let L^\dagger be the adjoint of L and it can be shown that a non-trivial solution h_n must exist to the problem $L_n^\dagger h_n = 0$, where

L_n^\dagger is evaluated at $s = s_n$.

$\therefore \langle Lf, g \rangle = \langle f, L^\dagger g \rangle$ on an inner product space;

$$\therefore \langle L_n f_n, h_n \rangle = 0$$

Taking the total derivatives with respect to the parameter α :

$$\frac{dS_n}{d\alpha} = - \frac{\frac{\partial}{\partial \alpha} \langle L f_n, h_n \rangle}{\frac{\partial}{\partial S_n} \langle L_n f_n \rangle},$$

Where only simple poles are considered, we can reduce the above to:

$$\frac{dS_n}{d\alpha} = \frac{\langle \frac{\partial L_n}{\partial \alpha} f_n, h_n \rangle}{\langle \frac{\partial L_n}{\partial S_n} f_n, h_n \rangle} \quad (1.5.16)$$

This will be of interest to us since the parameter α may be the polarization angle or the aspect angle. The variation of S_n with respect to, say the polarization angle, will only alter the residues.

It is found that the tracking of poles is not only difficult and expensive, but the poles are not stable when noise is present in the target. Noise is always present in the target, and so all the problems we found solved, hold, in a sense, for ideal cases only.

When composite targets are considered, an additional complication sets in. The coupling of composite parts are very difficult to ascertain, and one may only make some heuristic arguments about the coupling parameters, which in fact will require the introduction of higher order poles (Langenberg, 1983/-84, Sabatier, 1983/84).

1.5.5 Advantages and Some Drawbacks of SEM Formulations

Since the natural frequencies that characterize the target are independent of the input signal, we need to locate the poles only once for identification. It is also a very powerful technique for solving boundary value problems. Although numerous techniques (semi-analytic, eigenfunction expansion by separation of variables, asymptotic techniques, conformal transform techniques) have been used, the problem is not rigorously justified. The integral equations of the first kind encountered in SEM are not well defined in the sense of Hadamard, so regularization has to be introduced (Ramm 1980a; and Ramm 1980b)

In most of the work done on SEM, the properties of the integral operator are not specified and, therefore, the validity of the procedure and the results are in question.

The integral operator may not span all values of the space of the operator and hence, the search for poles in the matrix formulation presents a problem.

The coupling of incident field to the target is usually complex for composite targets. The equivalent circuit concepts help alleviate the situation to a certain extent, but it is still a difficult problem to tackle.

The question of the validity of the necessary and sufficient conditions of SEM has not been fully explored (Dolph and Cho 1980; Ramm 1980a).

1.5.6 Regge-Pole Theory and Possible Connections to SEM

The theory of complex angular momenta introduced into potential theory by Regge (1959) pictures (a family of poles) the sequence as due to the presence of a single pole whose position varies continuously with the angular momentum λ . That is, an infinite series of discrete terms is replaced by a contour integral of an analytic function (using the Watson-Sommerfeld Transform: Newton 1964; Chew 1966; Gottfried 1966).

In SEM, if we replace the complex wave number by the complex angle, the Sommerfeld contour is found to be a straight line, which facilitates the tracking of singularities which may be located between the original and the transformed paths.

The Regge poles have a signature that will tell if the pole is a particle, a resonant state, or a virtual state. The same idea is carried over in the SEM, where the characteristic poles and the target shape and size properties are related.

1.5.7 Prony's Method in a Noisy Environment

Extraction of the resonance poles in a noisy environment is a complex problem and alternate, modified Prony's methods have been suggested (van Blaricum 1981). This report summarized the various resonance extraction procedures and discusses how the SEM may be used for target identification. The presence of noise in data makes the problem of determining the order of a system very difficult. Either overestimation or underestimation of the system order leads to poles that deviate substantially from the true poles. However, procedures exist that give the order of the system in the presence of noise in data (van Blaricum 1981).

It is shown that when Prony's method is used indiscriminately (Dudley 1979) we have serious errors. Dudley (1979) considers an electromagnetic system, which he approximates by a single-input, single-output parameter linear model. The error norm in the data is minimized using the least squares technique. It is found that finding the pole position may be an ill-posed problem, and application of Prony's method leads to very serious errors, not only in positioning of the poles but also as regards the stability of the system.

1.5.8 Singularity Theory and Remote Sensing

The geometric singularities exhibited by reflected electromagnetic waves can be used to reconstruct the scatterer. The response can be reduced to a finite number of standard forms, and since remote sensing is structurally quite stable, reconstruction is effected with ease (Dangelmayr and Güttinger 1980; Kennaugh 1981). This technique is related to the geometric theory of diffraction (GTD).

Consider a spherical wave

$$\phi(t, x) = F(t - \frac{R}{c}) / 4\pi R \quad (1.5.17)$$

incident upon a perfectly reflecting surface at x and time t .

Within Kirchhoff's diffraction approximation, the scattered wave is given by

$$\psi(t, \underline{x}_0) = \frac{1}{8\pi^2 c} \int_S ds \left(\frac{\partial}{\partial n} \left(\frac{1}{R} \right) \right) \left\{ \frac{c}{R} F\left(t - \frac{2R}{c}\right) + F\left(t - \frac{2R}{c}\right) \right\}, \quad (1.5.18)$$

with ds as the element of surface area on the lit side, $\underline{n}(\underline{x})$ as the unit normal to the surface, and \dot{F} the rate of change of F .

If λ is small, then the area can be approximated by

$$\psi(t, \underline{x}_0) = \frac{1}{8\pi^2 c} \int_S ds \left(\frac{\partial}{\partial n} \left(\frac{1}{R} \right) \right) \dot{F}\left(t - \frac{2R}{c}\right) \quad (1.5.19)$$

We rewrite the above as

$$\psi(t, \underline{x}_0) = \frac{1}{16\pi^2} \int_0^\infty dr G'(r, \underline{x}_0) F\left(t - \frac{2r}{c}\right) \quad (1.5.20)$$

where $G' = \frac{\partial G}{\partial r}$ and

$$G(r, \underline{x}_0) = \int_S ds \delta(r-R) \frac{\partial}{\partial n} \frac{1}{R} = \int_S \frac{dS}{R^3} \underline{n} \cdot \underline{R} \delta(r-R) \quad (1.5.21)$$

G defines the surface geometry and G' is the wavefront sweep.

The wavefronts ϕ of constant radius r , centered at \underline{x}_0 , cuts the surface S in a series of contours $C(r, \underline{x}_0)$.

Summing over all these contours for all relevant r explores the surface. With retardation of the pulse taken into account, we get back the response (Marin 1974a).

1.5.9 Vector SEM

Next, we consider the vector SEM that will partially solve some of the problems. We treat the case of a thin wire, but the technique is quite general and we are working the the scattered matrix formulation of SEM. Again, only the Dirichlet condition is used.

First, consider \underline{E} in the plane of the paper. (We generalize it to the case where \underline{E} is out of the paper).

The current induced on the scatterer is given by

$$I(t, \theta, y) = \sum_i R_i(\theta, y) e^{s_i t} \phi(t, \theta, y) \quad (1.5.22)$$

We can write the residues as

$$R_i(\theta, y) = A_i N_i(\theta) M_i(y) \tilde{f}(s_i), \quad (1.5.23)$$

Where

$$\begin{aligned} A_i &= \text{constant} \\ N_i(\theta) &= [N_i(\theta, \psi)] = \text{normalized coupling coefficient} \\ M_i &= \text{normalized natural mode} \\ f &= \text{Laplace Transform of the exciting function} \end{aligned}$$

The natural modes M_i are independent of the incident angle but depend on the variable y . Later we shall introduce the conjugate modes that will facilitate the computation of the poles.

The natural modes can be approximated by the expression:

$$M_i(y) = \sin \frac{\pi y i}{L}, \quad i = 1, 2, \dots \quad (1.5.24)$$

The coupling coefficient describes how the incident field interacts with the scatterer and is independent of y , but is dependent on the aspect angle (and the polarization angle ψ).

The convolution form of the coupling coefficients are given by

$$N_i(\theta) = \frac{\langle M_i(r); I(r, s) \rangle}{\langle M_i(r); T_{1i}(r, r'); v_i(r) \rangle} \quad (1.5.25)$$

We approximate the coupling coefficients as

$$A_i f(s_i) N_i(\theta) = \int_0^L \sin \frac{\pi z_i}{L} \tilde{E}_y(y, s_i) dy, \quad (1.5.26)$$

where \tilde{E}_y is the Laplace Transform of the incident field tangential to the scatterer.

$$\tilde{E}_y(y, s_i) = f(s_i) \cos \theta e^{-s_i y} \sin \frac{\theta}{c} \quad (1.5.27)$$

(1.5.26) reduces to:

$$\begin{aligned} f(s_i) A_i N_i(\theta) &= \int_0^L \sin(i\pi y/L) f(s_i) \cos \theta * e^{-s_i y} \sin(\theta/c) dy \rightarrow \\ A_i N_i(\theta) &= \int_0^L \sin(i\pi y/L) \cos \theta e^{-s_i y} \sin(\theta/c) dy \end{aligned} \quad (1.5.28)$$

We choose, at this point, the input (exciting) waveform.

If we wait until the Gaussian pulse has passed through the scatterer, we can apply Prony's technique to analyze the problem. In this case, the forced response is set equal to zero.

Since we have scattered fields for two mutually orthogonal directions of incidence, we claim that there might be some poles for which the residues are independent of the noise characteristics of the targets.

Let T_N^1 and T_N^2 be the returns for 2 \perp^r set of incident fields for which we are interested in studying the properties.

$$\frac{R_N^2(\theta, \psi, s_i)}{R_N^1(\theta, \psi \pm \pi/2, s_i)} = \Gamma(s_i, \alpha) \quad (1.5.29)$$

That is, we postulate that for 2 \perp^r set of incident fields, the ratio of the noisy part of the target may be a constant Γ , but Γ will be a function of s_i .

It is assumed that all the poles are excited at the same time. But from physical considerations, it is obvious that this is not so; we consider the order of these poles at proper ringing times (we are looking at the problem of $s_i(t)$). The problem is slightly difficult because time dependence is removed by taking the Laplace Transform. We are looking at the problem of pole s_i excitation at time t_i and this makes the boundary value problem extremely difficult.

1.5.10 Multiple Poles in the Singularity Expansion Theory

The basic SEM technique utilizes the representation of the response function in terms of its singularities in terms of its Laplace Transform. The resonating frequencies are the manifestations of simple poles in the complex frequency domain. Most of the work on SEM has dealt with first order poles only as the interpretation is simple and easy enough to handle them both numerically and analytically.

Other types of singularities also arise. Branch cuts, and multiple-order poles are some of the other types of singularities that need to be looked into.

Branch cuts usually arise when we consider losses in the medium, or the idealized perfect-conductor case is replaced by near-perfect conductors. This case can be treated as surface perturbations in conducting properties of the scatterer.

Marin (1974b) has looked at the scattering from imperfectly and conducting bodies placed within a parallel plate region and finds that the singularities in the complex frequency domain are the simple poles and branch cuts.

The knowledge of the order of each pole is necessary in order to find the transient response of the scatterers. But no analytical techniques exist that can be used to determine the order of the pole whereas the order of the pole may be determined numerically as is shown in (Sabatier 1983; Langenberg 1983; Pearson 1981). The position of the poles might depend continuously on some parameter like the polarization angle; it is possible for some values of the parameters for two simple poles to coalesce into a second order pole. The inverse also holds: a second order pole might split into two simple poles (Baum 1974).

We consider the possibility of the existence of higher order poles to be important in the context of vector SEM, where the polarization angle of the incident field would serve as a continuous parameter in the case discussed

above. Higher order poles can also be obtained when the scattered fields are expressed as vector multi-pole expansion fields. Higher order poles may be realized in the geometric theory of diffraction (Dudley 1979). This is an important aspect of SEM in the case of penetrable scatterers.

The slope diffraction from a wedge gives rise to second order singularities. The incident field is the ray optical field given by:

$$x_0^i \sim \frac{e^{-jks'}}{\sqrt{s'}} f(\phi'')$$

The diffracted-scattered field is given by:

$$\begin{aligned} x^d(s) \sim & x_0^i(Q_E) D(\phi, \phi') \frac{e^{-jks}}{s} + \frac{1}{jks'} \frac{\partial}{\partial \phi''} x_0^i(Q_E) \frac{\partial}{\partial \phi'} D(\phi, \phi') \\ & - \frac{1}{2} \frac{\partial^2}{\partial \phi''^2} x_0^i(Q_E) D(\phi, \phi') - x_0^i D_1(\phi, \phi') \frac{e^{-jks}}{\sqrt{s}} \end{aligned}$$

The derivatives are evaluated at $\phi'' = 0$.

The slope diffraction contribution is the term:

$$\frac{1}{jks'} \frac{\partial}{\partial \phi''} x_0^i(Q_E) \frac{\partial}{\partial \phi'} D(\phi, \phi') \frac{e^{-jks}}{\sqrt{s}}$$

This structure is easily found to have second-order poles.

$D(\phi, \phi')$ is the diffraction coefficient for the wedge. The diffraction coefficient has a complicated structure given by

$$\begin{aligned} D(\phi, \phi') = & \frac{-e^{j\pi/4}}{2n\sqrt{2\pi k}} \frac{1}{\sin \beta'_0} * \cot \frac{\pi - \phi + \phi'}{2n} F(kL^i a^+(\phi - \phi')) + \\ & + \cot \frac{\pi - \phi + \phi'}{2n} F(kL^i a^-(\phi - \phi')) + \left(\cot \frac{\pi + \phi + \phi'}{2n} F(kL^{rn} a^+(\phi + \phi')) + \right. \\ & \left. + \cot \frac{\pi - \phi - \phi'}{2n} F(kL^{ro} a^-(\phi + \phi')) \right) \end{aligned}$$

with

$$F(x) = 2\pi j \sqrt{x} e^{jx} \int_{\sqrt{x}}^{\infty} e^{-jt^2} dt$$

$a \pm (\phi \pm \phi')$ are given in terms of trigonometric functions.

1.5.11 Self-Adjoint and Essentially Self-Adjoint Operators in Electromagnetic Theory

Let H be a Hilbert space and let A in S be an operator (S is a subspace of H). The operator A in S is self-adjoint if:

- (i) A in S is symmetric
- (ii) $(A+Ii)S = H$ and $(A-Ii)S = H$, where I is the identity operator.

The range of the operators $(A \pm Ii)$ in S is the entire space H .

Sometimes it is difficult to show the self-adjointness of the differential or integral operator we use in E-M field theory. We introduce therefore the concept of essential self-adjointness which meets our needs quite adequately.

An operator A in S is essentially self-adjoint if:

- (i) A is symmetric in S
- (ii) $(A \pm Ii)S$ are dense in the Hilbert space H .

A subset F is dense if for every $F \in M$:

- (a) F is a subset of M
- (b) for every x in M , there exists a sequence x_1, x_2, \dots, x_n $F \in M$ such that $\lim_{n \rightarrow \infty} x_n = x$.

Since A in S is symmetric, Ii cannot be eigenvalues of A in S .

Thus, since $(A \pm Ii)x = 0$, it follows that $x = 0$. Hence $(A \pm Ii)^{-1}$ exists and has dense domains of definition in H if A in S is essentially self-adjoint.

Such essentially self-adjoint operators can be extended to self-adjoint operators in a unique way.

Most operators in physics (EM field theory included) have all eigenvalues and eigenfunctions essentially in the subspace S of H in which the operators are only essentially self-adjoint.

We look at the EFIE and MFIE operators and consider the necessary and sufficient conditions for them to be essentially self-adjoint. Because it is found that the EFIE operator usually has eigenvalues and eigenfunctions that fall outside its subspace S , the interpretation lacks a correct explanation. Usually the interior resonances contribute to the solution, which is outside the range of the operator.

We hope to achieve a lot by replacing self-adjointness by essential self-adjointness. Another aspect of the problem that has been overlooked is the fact that the operators may not be totally self-adjoint or essentially self-adjoint but may be non-self-adjoint also.

1.5.12 Conclusion

The singularity expansion technique is a very powerful technique for handling most boundary value problems. As has been noted, several open problems in SEM exist that have either been partially solved or where solved, rigorous justification has not been made. The SEM can be applied to penetrable scatterers and has applications in acoustics, non-destructive testing of biological specimens, detection of cracks in structures by variation of pole location, etc. The dissertation write-up of the Ph.D. Thesis of V.M.S. Mirmira is in final preparation in which these aspects are treated in extensive detail.

1.5.13 References

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I.6 THE RECEIVED POWER: MUELLER MATRIX REPRESENTATION AND HUYNEN'S N-TARGET CHARACTERISTIC PARAMETER DESCRIPTION

In Boerner, Manson and Huynen (1983), it was shown that the received voltage $V(t)$ from a radar target, with scattering matrix $[S(T)]$, obtained by transmitting an elliptically polarized wave \underline{h}_T and using a receiver antenna with receiver polarization \underline{h}_R is given by

$$V(t) = [S(t)]\underline{h}_T \cdot \underline{h}_R \quad (1.6.1a)$$

It turns out that to this voltage equation, there corresponds a similar linear relationship for power received. Let $P = |V|^2$, then

$$P(t) = [M(t)]\underline{g}_T \cdot \underline{g}_R \quad (1.6.1b)$$

where $[M]$ is the 4x4 real-valued Stokes matrix (also called the Mueller matrix in optics) which represents the target in terms of power measurements, and $\underline{g}_T, \underline{g}_R$ are the Stokes vectors which correspond to the elliptically polarized antennas in power. Most often (in optics), the Stokes vector \underline{g} is given in geometrical parameters as follows:

$$\underline{g}(g_0, \phi, \tau) = \begin{bmatrix} g_0 \\ g_0 \cos 2\phi \cos 2\tau \\ g_0 \sin 2\phi \cos 2\tau \\ g_0 \sin 2\tau \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad (1.6.2)$$

The nomenclature given above supplies the same information as the polarization vector $\underline{h}(a, \alpha, \phi, \tau)$ defined in Chapter 2, with $g_0 = a^2$, except that the absolute phase α disappears with power measurements. Now the Stokes matrix $[M]$ can be made equally analogous to the scattering matrix $[S(A,B)]$ introduced in Chapter 2. We thus find:

$$[M] = \begin{bmatrix} A_0+B_0 & C & H=0 & F \\ C & A_0+B & E & G \\ H=0 & E & A_0-B & D \\ F & G & D & -A_0+B \end{bmatrix} \quad (1.6.3)$$

where

$$\begin{aligned} A_0 &= Q f \cos^2 2\tau_m \\ B_0 &= Q(1 + \cos^2 2\gamma - f \cos^2 2\tau_m) \\ B &= Q[1 + \cos^2 2\gamma - f(1 + \sin^2 2\tau_m)] \\ C &= 2Q \cos 2\gamma \cos 2\tau_m \\ D &= Q \sin^2 2\gamma \sin 4\tau_m \cos 2\tau_m \\ E &= -Q \sin^2 2\gamma \sin 4\tau_m \sin 2\tau_m \\ F &= 2Q \cos 2\gamma \sin 2\tau_m \\ G &= Q f \sin 4\tau_m \end{aligned} \quad (1.6.4)$$

$$Q = \frac{p_A^2 p_B^2 m^2}{8 \cos^2 \gamma} \quad (1.6.5)$$

$$f = 1 - \sin^2 2\gamma \sin^2 2\nu$$

Notice that the target orientation angle ψ does not appear in the defining equations of Huynen's characteristic target parameters A_0 to G . Instead it has been incorporated with the antennas \underline{g}_T and \underline{g}_R , where it appears as $\Phi = \phi - \psi$ instead of ϕ in $\underline{g}(g_0, \phi, \tau)$. This is an essential requirement for an approach to orientation-independent target discriminants. Hence all target parameters in $[M]$ defined above are orientation independent. It would be an easy matter to transform ψ back into the Stokes matrix. We would then obtain

$$[M_\psi(t)] = \begin{bmatrix} A_0+B_0 & C_\psi & H_\psi & F \\ C_\psi & A_0+B & E_\psi & G_\psi \\ H_\psi & E_\psi & A_0-B & D_\psi \\ F & G_\psi & D_\psi & -A_0+B_0 \end{bmatrix} \quad (1.6.6)$$

where:

$$\begin{aligned} H_\psi &= C \sin 2\psi \\ C_\psi &= C \cos 2\psi \\ G_\psi &= G \cos 2\psi - D \sin 2\psi \\ D_\psi &= G \sin 2\psi + D \cos 2\psi \\ E_\psi &= E \cos 4\psi + B \sin 4\psi \\ B_\psi &= -E \sin 4\psi + B \cos 4\psi \end{aligned} \quad (1.6.7)$$

We notice in particular that for a target on axis ($\psi=0$), $H_\psi=0$.

1.6.1 Target Structure Diagram

The target diagram is a pictorial representation of a single target, with orientation-bias ψ removed. The diagram is a result of the following three equations which are defined in detail in Huynen (1970, 1978, 1982a, 1982b):

$$\begin{aligned} Q_1 &= 2A_0(B_0 + B) - (C^2 + D^2) > 0 \\ Q_2 &= 2A_0(B_0 - B) - (G^2 + H^2) > 0 \\ Q_3 &= (B_0^2 - B^2) - (E^2 + F^2) > 0 \end{aligned} \quad (1.6.8)$$

For a single object (at given exposure-look, frequency, pulse shape, etc.) the right-hand sides of Q_1 to Q_2 are zero. This poses an interesting set of conditions. For example, let us assume that $A_0=0$ in Q_1 and Q_2 , then it must follow (because $Q_1-Q_2=0$) that $C=D=G=H=0$! Also, from these same equations we

find that B_0-B and B_0+B are non-negative. Hence we find if $B_0-B=0$ or $B_0=B$, then from Q_2 and Q_3 it follows (since $Q_2=Q_3=0$) that: $E=F=G=H=0$. Finally, if $B_0+B=0$, then by Q_3 and Q_1 : $E=F=C=D=0$. For these reasons the diagonal elements A_0 , B_0+B , and B_0-B are called the generators of the off-diagonal Stokes parameters. A_0 is the generator of target symmetry. $B_1=(B_0-B)/2$ is, in general, the generator of target non-symmetry (if $B_1=0$ or $B_0=B$ we have a symmetrical target), while $B_2=(B_0+B)/2$ is, in general, the generator of target irregularity (if $B_2=0$, the target is regular). From these two definitions we have:

$$B_0 = B_1 + B_2$$

which again emphasizes that B_0 is the sum total of non-symmetrical and irregular target components.

We are now ready to assemble all pieces of information obtained thus far on single target parameters into a complete structure diagram (Figure 1.7). The diagram shows a threefold symmetry between target parameters. The three structure generators are: A_0 , the generator of target symmetry; B_1 , the generator of target non-symmetry; and B_2 , the generator of target irregularity.

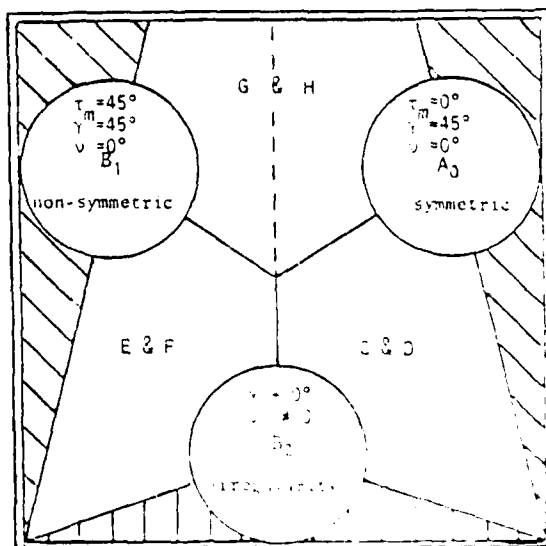


Figure 1.7: Target Structure Diagram for Single Radar Target.

Each generator is responsible for generating two pairs of adjacent off-diagonal parameters: thus, A_0 generates the pair C&D and G&H. We already mentioned C&D. The pair G&H are coupling terms. H is a measure of coupling due to target orientation ψ . We found that if $\psi=0$, then $H=0$; whereas G

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POLARIZATION UTILIZATION IN RADAR TARGET
RECONSTRUCTION: C-WIDE (MULTI-FR..(U) ILLINOIS UNIV AT
CHICAGO CIRCLE ELECTROMAGNETIC IMAGING DIV

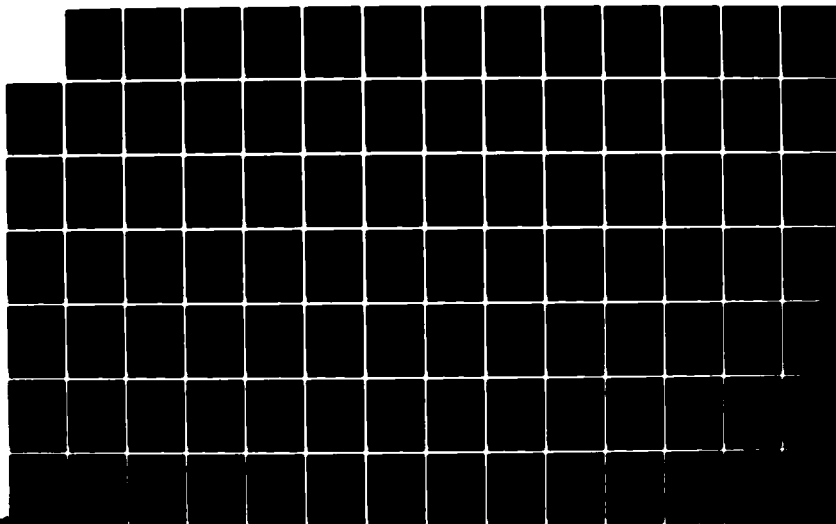
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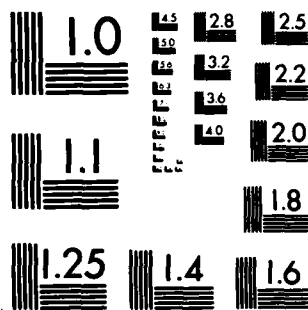
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MICROCOPY RESOLUTION TEST CHART
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couples the symmetric and nonsymmetric parts of the target: if $G=0$ (with $\phi=0$), then either the target is purely symmetric or nonsymmetric.

if $A_0=0$, then $C=D=G=H=0$ and we have the class of non-symmetric N-targets.

N-targets play an important role in the theory of distributed targets: There, they represent "residue" or "target noise" at the higher frequencies. N-targets produce the most asymmetric type of scattering (large helicity, $\tau_m = \pm 45^\circ$), such as produced by troughs, edged interacting surfaces, helices, etc. The single N-target is given by four parameters: $B_0 > 0$, B , E , and F , for which $B_0^2 = B^2 + E^2 + F^2$ (or $Q_3^N = 0$) as was discussed in greater detail in (Huynen 1978, 1982 a, b).

For a target 'on-axis', with $\phi=0$, the three generators have the following interesting relationships:

$$A_0 = Q f \cos^2 2\tau_m$$

$$B_1 = Q f \sin^2 2\tau_m$$

$$B_2 = Q(\cos^2 2\gamma + \sin^2 2\gamma \sin^2 2\nu)$$

with parameters defined previously. The first two equations are indicative for target symmetry or non-symmetry. The expression for B_2 shows that $B_2=0$, when the target is regular only if $\gamma=45^\circ$ and $\nu=0^\circ$, which defines convex or specular type of scattering.

1.6.2 Discussion of Target Parameters

The nine target parameters are of importance because they basically define a correlation matrix (after averaging). Secondly, they are model free, hence applicable to any radar target. And, thirdly, they exhibit genuine physical significance related to the target. The three basic parameters are the 'generators' $2A_0$, B_0-B , and B_0+B . Notice that the physical significance attached to these parameters is true for either beam-filled (coarse resolution) or high resolution targets. The former relates to averaged (integrated) global target characteristics, whereas the hi-resolution case focuses on target detail. Very fine detail is not always a desirable characteristic for target sorting, but will help for target identification purposes.

1.6.3 Description of Target Parameters

$2A_0$: Perhaps the most important parameter, and A_0 the generator of target symmetry

If $2A_0=0$, the target is non-symmetric or an N-target. It is associated with regular, smooth, convex types of surface scattering, which often contribute to specular returns. Since $2A_0$ is orientation independent (see Fig. 1.8), it serves as a good overall measure of target symmetry (for man-made targets). Incidentally, $2A_0$ is measured directly and simply by the (RC,LC) circularly polarized returns.

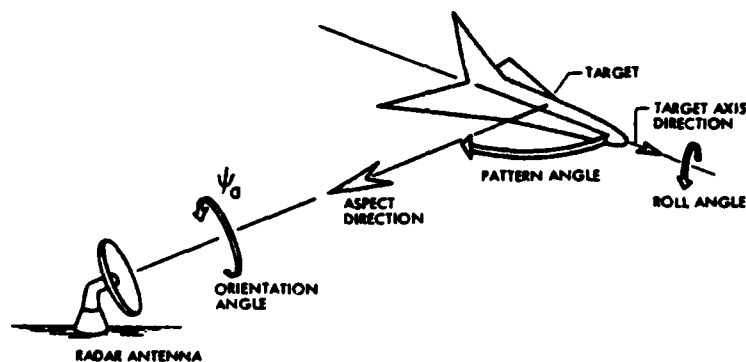


Figure 1.8: Target Aspect Direction and Orientation Angle
(Huynen, 1970, p. 37)

$B_0 - B$: is a measure of target non-symmetry. This parameter can generally be expected to be small for man-made objects (if $B_0 = B$ we have a symmetrical target on axis). It must be noted that $B_0 - B$ is a parameter that has been derived after the orientation effect ψ has been removed. Since $B_0 - B$ is given by

$$B_0 - B = 2Qf \sin^2 \tau_m, \quad \text{where } f = 1 - \sin^2 \gamma \sin^2 \nu$$

one can see that for a linear scattering matrix (Huynen, 1970: LSM) if $\tau_m \approx 0$, $B_0 - B$ will be zero and for $|\tau_m| = 45^\circ$; $B_0 - B \rightarrow 2Qf$. Thus, $B_0 - B$ shows the intrinsic non-symmetry of the object. It tells us that there is no intrinsic plane of symmetry dividing the object and, therefore, the cross polarization basis will be elliptical or circular.

$B_0 + B$: is a measure of target irregularity. This is because it is the generator of C, D, E and F, i.e. of off-diagonal terms of symmetrical as well as non-symmetrical parts of the target. Irregularity in conjunction with these other four parameters gives us important clues about the physical nature of the targets. For instance, for a line-target: $2A_0 = C = B_0 + B$, and we can expect high returns for these three plots in which case $(B_0 + B)$ is given by:

$$B_0 + B = 2Q(\cos^2 \gamma + \sin^2 \gamma \sin^2 \nu)$$

To get a better idea of what irregularity means, we must first define what regularity means in terms of a scattering matrix. If we take scattering measurements in a linear polarization base, and remove the Eulerian rotations ψ and τ_m we are left with a diagonal scattering matrix. If this

matrix can be represented in the form:

$$[S(H,V)] = m \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \phi \text{ and } \tau_m \text{ removed.}$$

where m is a constant, then the target is said to be regular (sphere, flat plate), if the two diagonal terms differ in phase, or amplitude, then the target contains irregularity. Thus, we can see from the equation for $(B_0 + B)$ that it is γ and ν that produce irregularity. If $\gamma \rightarrow 0^\circ$ or $\nu \rightarrow 45^\circ$, then irregularity becomes apparent. Gamma (γ), the target characteristic angle, makes the amplitudes between two co-polarized amplitudes (null locations) differ and ν makes the 2 co-polarized phases differ. Depending on the value of τ_m we see that irregularity has meaning for symmetrical ($\tau_m = 0$) or non-symmetrical ($\tau_m \neq 0$) targets. The target skip angle ν indicates the phase shift of the co-polarized returns and will indicate curvature variations at the specular point (Foo, 1982; Foo, Chaudhuri, Boerner, 1983) for convex targets or multibounce effects for targets like corner reflectors derived by Foo (1982) as

$$\frac{k_u - k_v}{2k} = -\tan \frac{\phi_{11} - \phi_{22}}{2},$$

where k_u, k_v represent the principal curvatures at the specular point and ϕ_{11}, ϕ_{22} the polarization phases of the S_{11}, S_{22} elements of $[S(1,2)]$, respectively.

C: is a measure of global shapes. For a sphere $C=0$, while for a line target $C=2A_0=B_0+B$ as indicated above. Since C is given by

$$C = 2Q \cos 2\gamma \cos 2\tau_m$$

we see that C measures global shape for predominantly symmetric targets. Examples of targets rendering high C values are long symmetric targets like dipoles that have linear scattering matrices of the form:

$$[S(H,V)] = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

D: is a measure of local shape for convex surfaces and it relates to the local radii of curvature of the specular point on the surface, i.e. $D=0$ if the local radii at the specular point are equal, but $D \neq 0$ if they differ. In general, D is small for man-made targets, but it can be large for a cylindrical surface at broadside (see M.Sc. thesis of Bing-Yuen Foo, 1982).

E: is a parameter related to target non-symmetry (torsion); it is usually small for man-made objects. The parameter E is analogous to parameter D except that E is most sensitive when the target has circular cross-polarization nulls; whereas, D is most sensitive when the target has linear cross-polarization nulls. E is given by:

$$E = -Q \sin^2 \gamma \sin 4\nu \sin 2\tau_m$$

It is the sine opposed to cosine relation that makes this parameter significant in a circular polarization base. E is sensitive to phase difference of the two co-polarized terms of a scattering matrix in a circular basis. E will be maximized if the relative scattering matrix in the circular basis is:

$$[S(LC,RC)] = \begin{bmatrix} +j/2 & 0 \\ 0 & -j/2 \end{bmatrix}$$

E, therefore, measures phase irregularity for targets that are non-symmetric.

F: is the target helicity parameter. It is measured directly through the difference in (RC-RC) and (LC-LC) polarized returns from the target (hence the term helicity, which relates to a preference for sense of circular polarization). F is analogous to the parameter C but is sensitive when one has circular cross polarization nulls. F responds to targets with circular x-pol nulls and with gamma type irregularity, i.e., with a scattering matrix of the form:

$$[S(LC,RC)] = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

Note, the similarity to the scattering matrix for a dipole in a linear base: "Targets giving rise to F may be imagined to be dipoles wrapped around in a helix".

G: is called the coupling parameter. It couples the symmetric and non-symmetric parts of the target. Usually G is small for man-made targets because the non-symmetric part usually is small. G is given by:

$$G = Q \sin 4\tau_m = Q(1 - \sin^2 2\gamma \sin^2 2\nu) \sin 4\tau_m$$

This shows that G is maximized when $\gamma = 0$, $\nu = 0$ and $\tau_m = 22.5^\circ$. This occurs at an ellipticity halfway between circular and linear polarization and shows that it is a transition or "coupling" parameter as one goes from a symmetric to a non-symmetric type of target or vice-versa. In the intermediate stages of distorting a linear dipole into a helix one can expect to see G rise and fall. A flat type of target with no plane of symmetry will produce a large G because there are no phase irregularities so that $\nu = 0$. This very specific property should enable us to see dynamic changes between oblate-to-spherical-to-prolate-spheroidal shape states and this must be a very important parameter in further developing radar meteorology (see M.Sc. thesis of Jerald D. Nespor, July 1983).

H_ψ : is the coupling due to target orientation ψ . Hence H_ψ can be made zero by properly aligning the roll of the target along the radar line of sight.

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1.7 MODEL-DEPENDENT AND MODEL FREE RADAR CLUTTER CHARACTERISTIC THEORIES

Experiments carried out in the last few years have demonstrated the relationship between the shape and orientation of a target and the location of its co-pol and cross-pol nulls. It has been observed that different types of clutter such as, for example, that of chaff, vegetation, sea waves, etc., have different clustering of the co-pol and cross-pol nulls about different mean polarization nulls. Thus, a detailed experimental study of the co-pol and cross-pol nulls of different types of targets and clutter and its dynamic polarization fork motion on the polarization sphere as functions of the aspect, frequency and time will provide a data base which is vitally needed for exploiting the full potential of radar polarimetry. In the following, the basic theory for such an approach is developed.

The backscattered radiation from the distributed target is usually always partially polarized. The polarization properties of a partially polarized wave can be determined by using the coherency matrix, or sometimes called intensity matrix, which is the Hermitian matrix introduced by Wolf (1965)

$$[J] = \begin{bmatrix} E_x & E_x^* & E_y & E_y^* \\ E_y & E_y^* & E_x & E_x^* \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \quad (1.7.1)$$

where E_x and E_y are the complex field components of the backscattered signal in the two orthogonally polarized channels.

The average backscattered power is given with : $X \triangleq 1$ and $Y \triangleq 2$ by:

$$\text{Tr}(J) = J_{11} + J_{22} \quad (1.7.2)$$

and the non-negative value of $\det(J)$ can be found to be

$$\det(J) = J_{11}J_{22} - J_{12}^2 > 0$$

A complex correlation factor between two orthogonally polarized channels can be given with $J_{12} = J_{21}$ by the degree of coherence μ :

$$\mu = |\mu| e^{j\beta} \frac{J_{12}}{\sqrt{(J_{11}J_{22})}^{1/2}} \quad (1.7.4)$$

As far as the polarization state of the backscattered wave is concerned, two extreme cases are of great interest: i) the wave is completely polarized if $\det([J]) = 0$, and ii) the wave is completely unpolarized if $J_{12} = J_{21} = 0$ and $J_{11} = J_{22}$. The wave in-between these two extreme cases is known as a partially polarized wave. It has been shown by Wolf [7] that such a wave may be uniquely expressed as the sum of two independent waves, one completely unpolarized and the other completely polarized. The partially polarized wave is represented by a point inside the Poincaré Sphere (Deschamps/Mast 1976) and the radius of the point is given by the degree of polarization P , ($0 < P < 1$), which is defined by:

$$P = 1 - \frac{4\det(J)}{(J_{11}+J_{22})^2} \quad (1.7.5)$$

The correlation between the two channels which is related to the degree of preferred orientation of the hydrometeor particles (McCormick, 1976) can be related to the degree of polarization by:

$$1 - P^2 = \frac{J_{11} J_{22}}{[1/2 (J_{11}+J_{22})]^2} [1 - |\mu|^2] \quad (1.7.6)$$

The partially polarized wave can also be characterized by four real quantities known as Stokes parameters (g_0, g_1, g_2, g_3). The Stokes parameters are related to the coherency matrix elements by the following relations:

$$\begin{aligned} g_0 &= J_{11} + J_{22} \\ g_1 &= J_{11} - J_{21} \\ g_2 &= J_{12} + J_{21} \\ g_3 &= J(J_{12} - J_{21}) \end{aligned} \quad (1.7.7)$$

The incident and received Stokes vectors can be related by the Mueller matrix [M]

$$\underline{g}_s = [M] \underline{g}_i \quad (1.7.8)$$

1.7.1 Optimal Polarization for Partially Polarized Signals:

The backscattered coherency matrix can be expressed in terms of the optimal scattering matrix elements (Nespor, M.Sc. Thesis, 1983). When polarization 1 is transmitted, the backscattered coherency matrix elements are given by:

$$\begin{aligned} J'_{S11} &= |S'_{11}|^2 \\ J'_{S12} &= \langle S'_{11} S'_{12}^* \rangle \\ J'_{S21} &= J'_{S12}^* \\ J'_{S22} &= \langle |S'_{12}|^2 \rangle \end{aligned} \quad (1.7.9)$$

For either J'_{S11} or J'_{S12} to be a minimum (at $J_{S12} = 0$), the optimal polarizations can be seen to be formally the same as for the completely polarized wave with S_{11}, S_{12} and S_{22} being replaced by their ensemble averages as illustrated in Figure 1.9:

$$\rho_{co} = \frac{-\overline{S}_{12} \pm \sqrt{\overline{S}_{12}^2 - \overline{S}_{11} \overline{S}_{22}}}{\overline{S}_{22}}$$

$$\rho_x = \frac{-\overline{b} \pm \sqrt{\overline{b}^2 - 4\overline{a}\overline{c}}}{2\overline{a}}$$

(1.7.10)

where

$$\overline{a} = \overline{S}_{22} \overline{S}_{12}^* + \overline{S}_{11}^* \overline{S}_{12}$$

$$\overline{b} = \overline{S}_{11}^2 - \overline{S}_{22}^2$$

$$\overline{c} = \overline{S}_{11} \overline{S}_{12}^* - \overline{S}_{22}^* \overline{S}_{12}$$

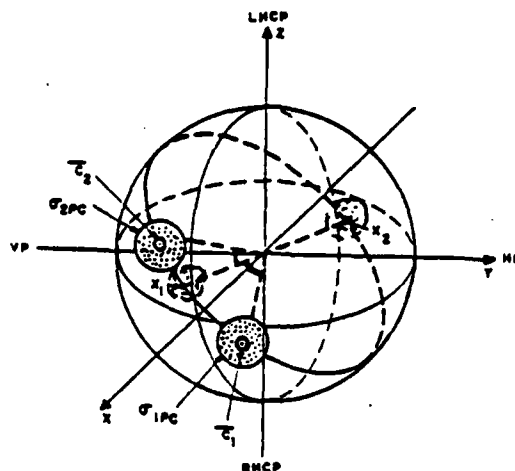


FIGURE 1.9: THEORETICAL REPRESENTATION:
OPTIMAL POLARIZATIONS ON
THE POINCARÉ SPHERE

The pair of the x-pol nulls may not always be antipodal on the Poincaré sphere as in the case of the completely polarized wave which requires further thorough theoretical analyses.

The variance of the co-pol null clustering for hydrometeors can be given by:

$$\sigma_{cp}^2 = \frac{1 - p^2}{2} \quad (1.7.11)$$

It is shown by Nespor (M.Sc. Thesis, August 1983) that this clustering of co-pol nulls is sensitive to the estimation of the scatterer shape distribution. In the case of hydrometeors being rain drops, the radar reflectivity weighted variance,

$\overline{\sigma_R^2}$ of \vec{R} for a polydisperse drop size distribution can be expressed in terms of σ_R^2 and Γ (the circular depolarization ratio) as:

$$\overline{\sigma_R^2} \approx 1.95 \sigma_{cp}^2 [1 + 2 (10^{\Gamma/10}) + (10^{\Gamma/10})^2]. \quad (1.7.12)$$

From the above discussion it is clear that the theory developed for optimal polarization null description of the single targets can be applied for classification and identification of distributed targets such as rain, hail, snow, etc., and it can straight-forwardly be extended to a model-free description of clutter as is shown in Nespor, Agrawal and Boerner (1983-1984) and was also attempted in Stock (1983-84).

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1.8 BASIC CONCEPTS OF POLARIMETRIC VECTOR RADIATIVE TRANSFER THEORY

(List of symbols presented at the end of section 1.8)

The radiative transfer equation, which governs the variation of intensity in a medium, that emits, absorbs and scatters radiation, can be written in its general form as (Chandrasekhar, 1960)

$$\underline{\Omega} \cdot \nabla I(\underline{r}, \underline{\Omega}) = -\Sigma(\underline{r}) \{I(\underline{r}, \underline{\Omega}) - J(\underline{r}, \underline{\Omega})\} \quad (1.8.1)$$

with

$$J(\underline{r}, \underline{\Omega}) = \frac{A(\underline{r})}{4\pi} \int_{4\pi} P(\underline{r}; \underline{\Omega}, \underline{\Omega}') I(\underline{r}, \underline{\Omega}') d\omega' + J(\underline{r}, \underline{\Omega}) \quad (1.8.2)$$

where $J(\underline{r}, \underline{\Omega})$ is the source function, and is composed of two parts: the first part due to multiple scattering and the second, $J(\underline{r}, \underline{\Omega})$, representing internal source(s).

In equations (1.8.1) and (1.8.2)

$I(\underline{r}, \underline{\Omega})$ = intensity at a point \underline{r} and in $\underline{\Omega}$ direction (see Figure 1.10)

$\Sigma(\underline{r})$ = the extinction coefficient, defined as the sum of the scattering and absorption coefficients, i.e.

$$\Sigma = \Sigma_s + \Sigma_a$$

$$A(\underline{r}) = \frac{\Sigma_s}{\Sigma} = \text{single scattering albedo}$$

$p(\underline{r}; \underline{\Omega}, \underline{\Omega}')$ = normalized scattering phase function, characterizing the angular distribution of the scattered intensity at \underline{r} .

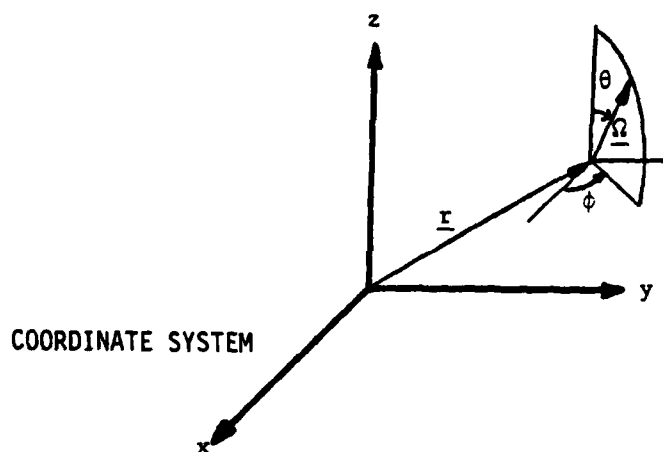


FIGURE 1.10

For convenience, we have suppressed the notation for frequency dependency of the quantities in Equations (1.8.1) and (1.8.2). All these quantities, in general, are temperature dependent.

A complete solution of the general radiative transfer problem requires the knowledge of the temperature, intensity and physical properties at every point within the medium. This is inherently a complex problem, and at present, no general solution to the equation of transfer (1.8.1) is available (Khounsary, 1981). However, depending on the specific problem under consideration, there are various simplifying assumptions (e.g. with regard to its geometry, radiative properties, etc.) and/or approximate techniques (e.g. mathematical manipulations, including series and asymptotic expansions) that can be used to obtain approximate - and in a few specific cases exact - solutions to the equation of transfer (Siegel and Howell, 1981; Ishimaru, 1978; Sobolev, 1963; Chandrasekhar, 1960; Lenoble, 1977).

For completeness, it should be added that the statistical Monte Carlo method (Plass and Kattawar, 1968) can be used to solve general radiative transfer problems to any desired degree of precision. This, however, is done not by solving the radiative transfer equation, but rather, by statistical consideration of the interactions of photons within a given medium. Exorbitant computation time is the major disadvantage of this method.

Multi-dimensional radiative transfer problems are particularly difficult to solve (Crosbei and Linsenbrandt, 1978; Scholand, 1981) and, whenever possible, one-dimensional approximates should be considered (Davies, 1978). Even then, solutions in most cases are approximate and require considerable efforts, especially so if polarization is included. We will discuss this problem in a later section.

1.8.1 Equation of Transfer in Plane Parallel Media

As stated earlier, in order to tackle the equation of transfer (1.8.1), certain simplifying assumptions regarding the geometry and/or properties of the medium under consideration must be made. These assumptions, however, should be such that a solution to (1.8.1) be both possible and meaningful.

In many radiative transfer problems (in the atmosphere, for example) a plane-parallel geometry can reasonably be assumed. As such, the problem is one-dimensional and all quantities in equations (1.8.1) and (1.8.2) will be functions of the remaining coordinate commonly denoted by z . The medium is said to be a horizontally homogeneous (vertically inhomogeneous) plane-parallel one, with intensity $I(z, \Omega)$ (Fig. 1.11).

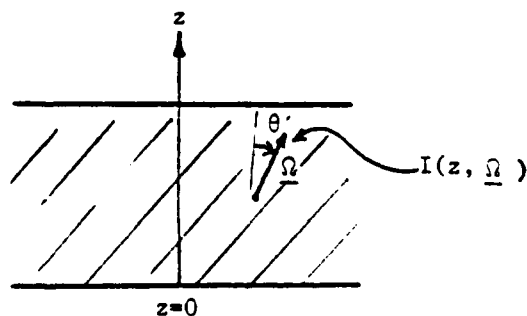


FIGURE 1.11

COORDINATES FOR THE PLANE PARALLEL MEDIUM PROBLEM

If Σ , A and P are independent of z , the medium will be totally homogeneous. In addition, if scattering is isotropic, i.e., $p(\underline{\Omega}, \underline{\Omega}')$ is independent of direction, we will have the simplest problem of multiple scattering, that of an isotropic homogeneous plane-parallel medium. In what follows, however, a finite anisotropic horizontally homogeneous plane-parallel medium, with no internal sources, is assumed. As such, the equation of transfer becomes (Chandrasehkar, 1960)

$$\cos \theta \frac{dI(z; \theta, \phi)}{\Sigma dz} = -I(z; \theta, \phi) + \frac{A(z)}{4\pi} \int_{4\pi} P(\theta, \phi; \theta', \phi') I(z; \theta', \phi') d\omega' \quad (1.8.3)$$

which upon introduction of the normal optical depth τ

$$\tau = \int_{z=0}^z \Sigma(z') dz' \quad (1.8.4)$$

and letting $\mu = \cos \theta$, becomes:

$$\mu \frac{dI(\tau; \mu, \phi)}{d\tau} = I(\tau; \mu, \phi) - \frac{A(\tau)}{4\pi} \int_0^{2\pi} \int_{-1}^1 P(\mu, \phi; \mu', \phi') I(\tau; \mu', \phi') d\mu' d\phi' \quad (1.8.5)$$

Equation (1.8.5) is the standard equation of radiative transfer in plane parallel media. Numerous solution procedures for this problem are available. They include analytical, computational, statistical and asymptotic methods (Lenoble, 1977). Some of the solution procedures are exact in the sense that at the expense of a prolonged computational time, any degree of accuracy is attainable. Examples are the already mentioned, statistical Monte Carlo and the computational doubling methods (Cogley and Sharma, 1979).

We can now proceed with inclusion of polarization into the radiative transfer equation in plane-parallel media without undue complications. It should be noted, however, that in most of the solution procedures for the plane-parallel media problem, polarization has been ignored, because in many instances, it has not been worth the effort or else, polarization information has been of little or no significance, as is the case, for example, in the area of radiative heat transfer (Siegel and Howell, 1981). Needless to say, that for a complete solution of the radiative transfer problem we must include polarization. This is indeed imperative in the case of modern radar and communication systems operated within the m-to-submm wavelengths region where de/re/cross-polarization effects in heterogeneous media cannot be neglected.

1.8.2 Equation of Transfer in Plane-Parallel Media with Polarization

When polarization is included in the radiative transfer equation for plane-parallel media, the scalar parameters of equation (1.8.5) become matrices. Introducing the modified Stokes vector $[I]$, (in this section 1.8, brackets are used for matrix notation) we can write the equation of transfer in homogeneous plane-parallel media as (Ishimaru, 1983):

$$\frac{d}{ds} [I] = [\Sigma] [I] + \int_{4\pi} [S] [I'] d\omega' \quad (1.8.6)$$

where

$$[I] = \begin{bmatrix} I_1 \\ I_2 \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_1 E_2^* \rangle \\ \langle E_2 E_1^* \rangle \\ 2\text{Re} \langle E_1 E_2^* \rangle \\ 2\text{Im} \langle E_1 E_2^* \rangle \end{bmatrix} \quad (1.8.7)$$

I_1 , I_2 , U and V are the modified Stokes parameters defined by (1.8.7), E_1 and E_2 are the orthogonal electric field components, and angled brackets denote ensemble averages.

Also in equation (1.8.6), $[\Sigma_{ij}]$ and $[S_{ij}]$ ($i, j = 1, 2$) are the extinction and scattering (Mueller) matrices and $[I']$ is the Stokes vector pointing in the direction $\hat{s}'(\mu', \phi')$ as shown in Figure 1.12, ds is the differential distance along \hat{s} .

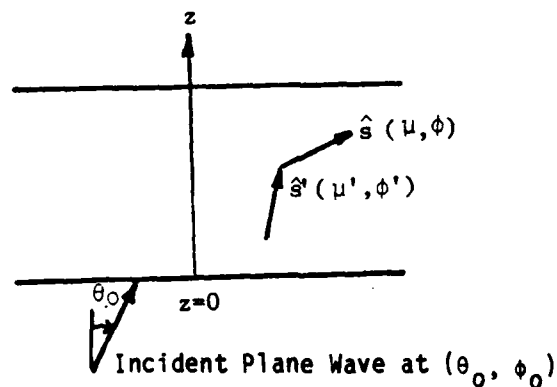


FIGURE 1.12
TRANSMITTED WAVE COORDINATES

It is a matter of convenience to divide the Stokes vector $[I]$ into two parts; the coherent (reduced, average, or direct) Stokes vector $[I_c]$ and the diffuse (incoherent, fluctuating or indirect) Stokes vector $[I_d]$, i.e.,

$$[I] = [I_c] + [I_d] \quad (1.8.8)$$

The coherent Stokes vector at a point in the medium represents that part of the source Stokes vector that has survived scattering and absorptions along the way. It is simply an exponentially delaying term given by:

$$\frac{d[I_c]}{ds} = [\Sigma] [I_c] \quad (1.8.9)$$

Using (1.8.9) and substituting (1.8.8) into (1.8.6), gives:

$$\frac{d}{ds} [I_d] = [\Sigma] [I_d] + \int_{4\pi} [S] [I'_d] d\omega' + [I_{cs}] \quad (1.8.10)$$

where $[I_{cs}]$ represents that part of the (as of yet) coherent Stokes vector at a point z in the medium that has just been scattered into direction \hat{s} ; it is given by:

$$[I_{cs}] = \int_{4\pi} [S] [I'_c] d\omega' \quad (1.8.11)$$

Denoting the direction of incident by \hat{i} , equation (1.8.11) can be written as

$$[I_{cs}] = [S(\hat{s}, \hat{i})] [I_c(\underline{z}, \hat{i})] \delta_{\hat{s}, \hat{i}} \quad (1.8.12)$$

where;

$$\delta_{\hat{s}, \hat{i}} = \begin{cases} 1 & \text{if } \hat{i} \equiv \hat{s} \\ 0 & \text{otherwise} \end{cases}$$

In the following section, we will briefly describe the parameters in equation (1.8.10). This equation governs the variation of the diffused Stokes vector $[I_d]$.

1.8.3 Extinction Matrix $[\Sigma]$

For spherical particles, and for non-spherical particles with random distribution, the total cross-section does not depend upon the polarization of the incident wave and, therefore, the extinction matrix reduces to a scalar extinction coefficient, Σ :

$$\Sigma = \int_0^{\infty} \sigma_t(D) n(D) dD \quad (1.8.13)$$

where $n(D)$ is the particle size distribution and $\sigma_t(D)$ is the total cross-section of a particle of size D . In general, $[\Sigma]$ is a 4x4 matrix which is derived in the following.

As the coherent wave propagates, the depolarization effects due to non-spherical particles can be obtained by writing the differential equation for the E_1 and E_2 fields along the propagation direction \hat{s} (Oguchi, 1983):

$$\frac{d}{ds} [E] = [M][E] \quad (1.8.14)$$

where

$$[E] = \begin{bmatrix} E_1 \\ E_2 \end{bmatrix},$$

$$[M] = [M_0] + [M']$$

$$[M_0] = (-ik) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$[M'] = i \frac{i2\pi}{k} L \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix} \equiv i \frac{2\pi}{k} L[F] \quad (1.8.15)$$

L is an integral operator, operating on all elements of [F], e.g.,

$$L f_{11} = \int_0^\infty f_{11} n(D) dD \quad (1.8.16)$$

where n(D) is the scatterer size distribution. [F] in equation (1.8.15) is the forward scattering amplitude matrix given by

$$[E_s] = \frac{e^{ikr}}{R} [F][E_i] \quad (1.8.17)$$

Where [E_s] and [E_i] are, respectively, the scattered and incident fields for a single scatterer, and R is the distance from the origin.

Evaluation of [M'] involves substitution of [F] defined in (1.8.17) into equation (1.8.15). [F] in both equations must be in the same coordinate system. This often requires some coordinate transformations.

The extinction matrix [Σ] is then given by (Ishimaru, 1983)

$$[\Sigma] = \begin{bmatrix} 2\text{Re } M_{11} & 0 & \text{Re } M_{12} & \text{Im } M_{12} \\ 0 & 2\text{Re } M_{22} & \text{Re } M_{21} & -\text{Im } M_{21} \\ 2\text{Re } M_{21} & 2\text{Re } M_{12} & \text{Re}(M_{11} + M_{22}^*) & -\text{Im}(M_{11} + M_{22}^*) \\ -2\text{Im } M_{21} & 2\text{Im } M_{12} & \text{Im}(M_{11} + M_{22}^*) & \text{Re}(M_{11} + M_{22}^*) \end{bmatrix} \quad (1.8.18)$$

1.8.4 Scattering Matrix [S]

In terms of the scattering amplitudes defined in (1.8.17), the scattering matrix is given by (Ishimaru, 1983)

$$[S] = L \begin{bmatrix} |f_{11}|^2 & |f_{12}|^2 & \text{Re}(f_{11}f_{12}^*) & -\text{Im}(f_{11}f_{12}^*) \\ |f_{21}|^2 & |f_{22}|^2 & \text{Re}(f_{21}f_{22}^*) & -\text{Im}(f_{21}f_{22}^*) \\ 2\text{Re}(f_{11}f_{21}^*) & 2\text{Re}(f_{12}f_{22}^*) & \text{Re}(f_{11}f_{22}^* + f_{12}f_{21}^*) & -\text{Im}(f_{11}f_{22}^* - f_{12}f_{21}^*) \\ 2\text{Im}(f_{11}f_{21}^*) & 2\text{Im}(f_{12}f_{22}^*) & \text{Im}(f_{11}f_{22}^* + f_{12}f_{21}^*) & \text{Re}(f_{11}f_{22}^* - f_{12}f_{21}^*) \end{bmatrix} \quad (1.8.19)$$

where L is the integral operator defined in (1.8.16)

Equation (1.8.19) represents the general formulation of the scattering matrix for non-spherical scatterers. Considerable simplification results if spherical scatterers are considered. In that case, the scattering amplitudes can readily be expressed in terms of the Van de Hulst scattering functions (Van de Hulst, 1957).

Now that every term of (1.8.10) has been defined, we focus our attention on the solution of the radiative transfer equation (1.8.10).

1.8.5 Solution of the (Diffused) Vector Radiative Transfer Equation

Equation (1.8.10), as it stands, contains five variables, namely τ , (θ, ϕ) , and (θ_0, ϕ_0) . Depending on the shape of the scatterers, direction of the incident wave and its state of polarization some of these variables can be eliminated, rendering the solution to (1.8.10) less involved.

For spherical scatterers, for example, with a circularly polarized and normally incident wave, only three of the five variables remain. The extinction matrix becomes a scalar and the Stokes parameters (I_1, I_2) and (U, V) decouple which can then be treated separately. Using one of the already mentioned solution procedures for the plane-parallel problems (Lenoble, 1977), i.e., the analytical eigenvalue method, the resulting equations for (I_1, I_2) and (U, V) have been solved (Ishimaru and Chung, 1980). The same problem, but for unpolarized, instead of circularly polarized incident waves, has also been solved (Ishimaru, 1981).

These cases, however, are among the simpler problems in radiative transfer, for only homogeneous plane-parallel media, without internal sources, have been considered and only for spherical scatterers have results been obtained. Approximate solutions for plane-parallel media with ellipsoidal scatterers (Tsang, 1981) and with internal emission and rough surfaces (Fung and Chan, 1981; Fung and Eom, 1981, 1983/84) have also been reported.

How general a plane-parallel vector radiative problem can be, and yet solvable, depends largely of the accuracy and efficiency of any proposed solution procedure. One of the solution procedures for plane-parallel media, which by all accounts has been shown to be fast, accurate with controlled error and yet efficient, is the doubling method due to Van de Hulst (1963). He showed that this method is a solution for a plane-parallel multiple scattering

medium of optical depth τ is known, this solution can be used to obtain the solution for layers of optical depths 2τ , 4τ , etc.

For the relatively simple case, in which polarization is neglected, the method has been used to obtain the transmission and reflection (Hansen, 1969) and the internal radiative fields (Hunt and Grant, 1969). Extension to inhomogeneous plane-parallel media, including an error analysis has also been reported (Sharma, 1980).

The doubling method has also been extended to include polarization in homogeneous plane-parallel media for the evaluation of the reflection and transmission functions (Hansen, 1971). The same method has been used to obtain the internal vector radiative field with an isotropic phase matrix assumed (Domke and Yanovitsky, 1981).

Due to the efficiency, accuracy and versatility of the doubling method, our immediate plan is to develop this method to solve the vector radiative transfer problem in plane-parallel media for the more general case of anisotropic scattering with arbitrary direction and state of polarization.

1.8.6 Continuing Research Studies

It is obvious by now that we have been very selective in the type of problems we discussed here.

In fact, in contrast to our simplifying assumptions, it is known that not all media of interest are plane-parallel, that the scatterers are not generally spherical, and that the incident wave may have arbitrary direction and state of polarization. Furthermore, suitability and applicability of the radiative transfer theory, as far as any given medium is concerned, should be investigated. These considerations suggest:

- 1) Investigation in extending the doubling method to media with geometries other than plane-parallel, inclusion of internal sources and consideration of various boundary conditions and rough surfaces;
- 2) evaluation of the radiative properties of media composed of non-spherical scatterers with or without random orientation;
- 3) consideration of obliquely incident wave with arbitrary state of polarization on plane-parallel media or upon other geometries of interest;
- 4) and establishing the limits of applicability of the equation of transfer to dense multiple scattering media, and the possibility of incorporating the shadowing effects.

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Nomenclature used in Section 1.8

$A(r)$	=	single scattering albedo
D	=	particle size scale, usually diameter
ds	=	differential distance along \hat{s} direction
E_1, E_2	=	orthogonal electric field components
$[E]$	=	electric field vector
$[E_i]$	=	incident field vectors
$[E_s]$	=	scattered field vector
$[F]$	=	scattering amplitude matrix
f_{ij}	=	elements of $[F]$
\hat{i}	=	unit vector along the direction of incident
I_1, I_2, U, V	=	modified Stokes parameters

$I(\underline{r}, \underline{\Omega})$	=	total intensity at point \underline{r} in $\underline{\Omega}$ direction
$[I]$	=	total Stokes vector
$[I_c]$	=	coherent Stokes vector
$[I_{cs}]$	=	coherent Stokes vector just scattered defined in (1.8.12)
$[I_d]$	=	incoherent Stokes vector
$J(\underline{r}, \underline{\Omega})$	=	source function defined in equation (1.8.2)
$(\underline{r}, \underline{\Omega})$	=	internal source function
L	=	integral operator
M_{ij}	=	elements of $[M]$
$[M]$	=	2x2 matrix defined in (1.8.14)
$[M_0]$	=	2x2 matrix defined in (1.8.14)
$[M']$	=	2x2 matrix defined in (1.8.15)
$n(D)$	=	particle size distribution
$p(\underline{r}, \underline{\Omega}, \underline{\Omega}')$	=	scattering phase function
\underline{r}	=	vector position
R	=	distance from coordinates origin
\hat{s}, \hat{s}'	=	unit direction vectors
$[S]$	=	scattering Mueller matrix
z	=	coordinate axis
θ, θ'	=	polar angles
θ_0	=	incident polar angle
μ	=	$\cos\theta$
$\sigma_t(D)$	=	total scattering cross-section
$\Sigma(\underline{r})$	=	Extinction coefficient
Σ_a	=	absorption
Σ_s	=	scattering coefficient
$[\Sigma]$	=	extinction matrix
τ	=	optical depth
ϕ, ϕ'	=	azimuth angles
ϕ_0	=	incident azimuth angle
$d\omega'$	=	differential solid angle
$\underline{\Omega}$	=	unit direction

I.9 APPLICATION 1: POLARIMETRIC DOWN-RANGE IMAGING USING KENNAUGH'S AND HUYNEN'S TARGET CHARACTERISTIC POLARIMETRIC OPERATOR THEORIES

In the following, basic polarimetric backscattering characteristics of simple to increasingly more complex shaped missile-type targets are analyzed and interpreted by strictly adhering to Kennaugh's target characteristic operator concept and Huynen's target Mueller matrix decomposition theories which were previously introduced. Scatterer model data were computer-generated on the DEC-VAX 11/750 Research Computer Processing System of the Communications Laboratory, Electrical Engineering & Computer Science Department, University of Illinois at Chicago, and compared with measurement data for missile-type composite targets by Teledyne Micronetics, collected on their S-band (2.4 to 3.975 GHz in steps of 25 MHz) and X-band (9.0 to 10.575 GHz) outdoor facilities for vertical (V) and horizontal (H) antenna polarization bases as described in

L.A. Morgan, S. Weisbrod, High Resolution RCS Matrix Studies of Simple Targets, Report Number NADC 83016, June 30, 1982,

and measurement data tapes were provided by:

Ray Dalton and Otto Kessler, NADC, in late December 1982.

Major emphasis is placed on extracting basic polarimetric scattering/diffraction centers of single isolated composite complex targets (missile shapes) and of two body multi-scattering center interaction systems which contribute to the overall optimal characteristics as functions of aspect and frequency, as well as incremental downrange resolution. The obtained results are reinterpreted with the objective of assessing the potential of complete polarimetric target downrange signatures as input functions for target characteristic classifiers.

1.9.1 Note on Downrange Resolution

In order to isolate a specific feature, the stepped frequency data were transformed to the time domain in order to "range gate" undesired and/or desirable features. For example, by means of this polarimetric downrange (slant) mapping procedure, it is possible to separate the returns due to a slot or a fin from the returns due to the end caps of the elongated missile target in which the slot is cut or to which the fins are attached, respectively. Because of the finite range resolution of the system as explained below, it is not possible to isolate completely the features on the cylinder near broadside aspect (zero degree pitch and 90° or 270° yaw). For this reason most data interpretations need to be confined to about plus or minus 60° from the end-on aspect.

The scattering matrix data is collected in the S-band at 64 frequencies in steps of 25 MHz, spanning the range 2.4 to 3.975 GHz (Correspondingly, 12.5 cm (4.92 inches) to 7.55 cm (2.97 inches) wavelengths). The total bandwidth is thus 1.575 GHz. The 64-point data are padded on to 128 points for FFT processing to obtain downrange plots of the scattering matrix elements. For a matched filter ($\Delta\tau = 1.2/2\Delta f$), the range resolution between the successive range points is given by:

$$\Delta R = c \frac{\Delta\tau}{2} = 2.249 \text{ inches for } \Delta\tau = 1.2/(2\Delta f) = .3809 \text{ nsec.} \quad (1.9.1)$$

This interpretation agrees with the separation of target peaks in the data which arise from scattering from the front and rear ends of the cylindrical target.

Thus, the different peaks occurring in the down range plots can be identified with the location of the specific features on the targets.

However, the resolution is governed by the windowing of the frequency-domain data. The FFT uses a Hamming window which tapers the frequency-domain data according to the function $w(f)$ given by:

$$w(f) = 0.54 + 0.46 \cos \frac{2\pi(f-f_0)}{\Delta f} \quad (1.9.2)$$

where f_0 is the center frequency and Δf is the bandwidth. The purpose of the Hamming window is to reduce the sidelobes in the range-domain which would be unacceptably large if a rectangular window is used. As a result of the use of the Hamming window, the sidelobes are reduced but the main beam broadens, thereby reducing the resolution such that at the ± 3 dB points we expect a broadening of 40% and, at the ± 10 dB level, of 100% which we found to correspond with the data we had analyzed.

As a measure of the resolution achievable with the Teledyne-Micronetics S-band data, the HH and VV downrange plots for a flat plate target are plotted in Figure 1.13 for target case 57 (Manson et al, 1983). The flat plate is a 17 cm radius circular disk. The HH and VV plots show a 10 dB width of about 12 inches and a maximum range sidelobe of about -21 dBs.

The measurements made are therefore not capable of detecting features much smaller than about 6 inches. Thus, the results for broadside measurements (yaw=90°) result in a single peak. However, for smaller yaw angles, individual features such as the wings, ducts or scoops, and fins can be easily identified.

1.9.2 Analysis of Target Downrange Data

The objective of the data analysis program is to generate and display data in a format which assists in identification of target features and in the development of classification algorithms. For this reason, we have used the raw data to generate and plot:

- (a) the HH, VV, HV and span plots as functions of range,
- (b) the polarization fork parameter, including the values of the Eulerian rotation angles and plots of the polarization fork on the Poincaré sphere, and
- (c) the nine elements of the Mueller matrix, the so-called Huynen parameters, as functions of the range.

To distinguish target features from clutter, only range cells where the response is at least 20 dB above the clutter are chosen. range cells which fall within 3 dB of these peaks are considered. The details of the techniques of implementing these plots are described in (Boerner, Manson, Huynen 1983, Chapter 4).

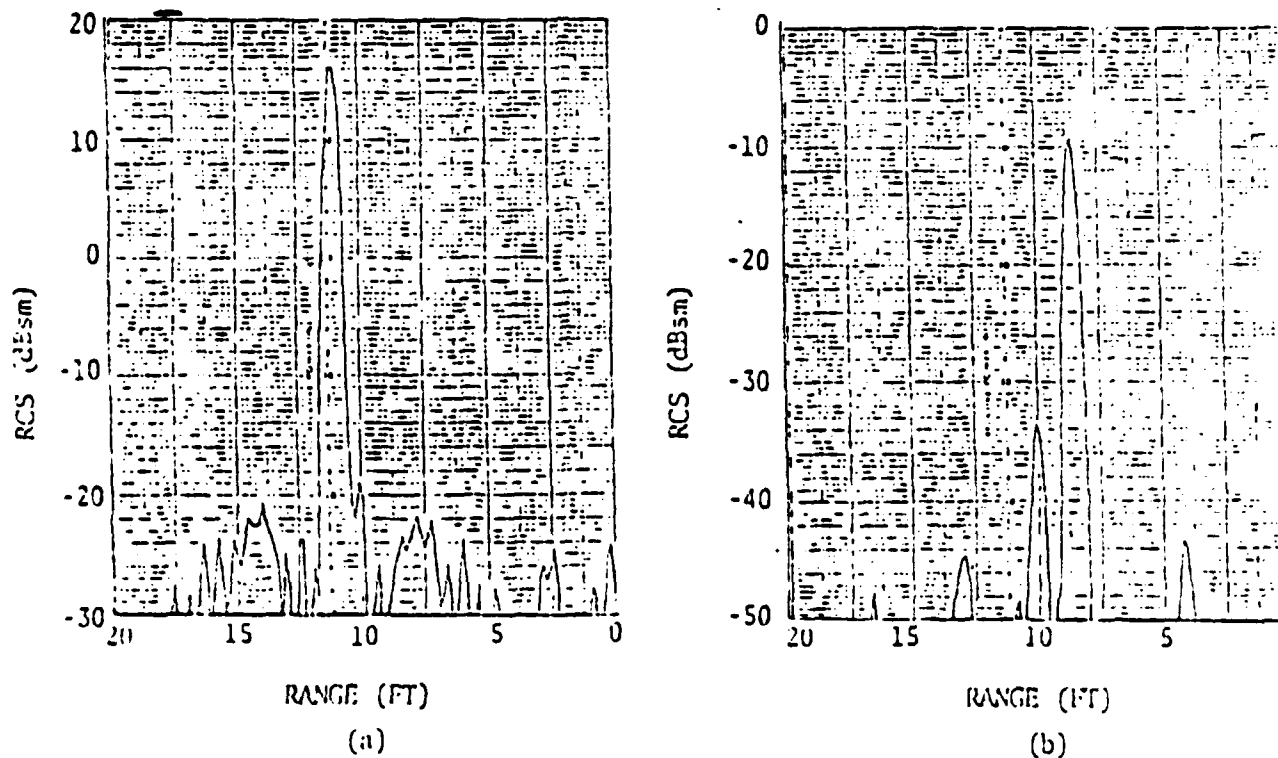


FIGURE: 1.13
HH and VV RCS Down Range Plots for a Flat Plate Calibration Target
(Target Case 57)
(borrowed from Morgan & Weisbrod 1982 Report, Fig. 3)

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I.10 APPLICATION II: MODEL-FREE DESCRIPTION OF RADAR CLUTTER AND ITS APPLICATION TO RADAR METEOROLOGY, REMOTE SENSING OF THE MARINE/TERRESTRIAL BOUNDARY LAYER

1.10.1 Introduction

Polarization, along with amplitude, frequency, phase and doppler, are the five parameters that completely describe an electromagnetic wave. In propagation through a precipitation medium, the polarization state can be the parameter most significantly changed. Due to engineering limitations prior to the last decade, such as achieving high polarization purity within an antenna beam, coupled with the lack of theoretical development, polarization diversity techniques applied to radar meteorology have had a low level of research effort.

There has, however, been substantial progress within the last decade with the development of theory for predicting and interpreting backscatter and propagation measurements and with the construction of antennas with good polarization characteristics, as well as fast polarization switching techniques.

As the scope of research relating to polarization has increased, new ideas for meteorological applications have been proposed. It is the expressed objective of the authors of this paper to suggest an integrated approach to "polarization diversity techniques" which have the possibilities of adding greater insight and reliability to meteorological identification and classification of different precipitation states based upon a complete polarization scattering matrix approach.

1.10.2 The Scattering Matrix

It was first shown by Sinclair (1948, 1950) that a radar target acts like a polarization transformer which is described by its associated scattering matrix [S]. At the target scatterer, then, the target scattering matrix characterizes the scattering properties of the target such that the scattered electric field can be related to the incident electric field by:

$$\begin{bmatrix} E_{s1} \\ E_{s2} \end{bmatrix} = \frac{\exp(-j k_0 r)}{r} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} E_{i1} \\ E_{i2} \end{bmatrix} \quad (1.10.1)$$

where the subscripts s and i refer to the scattered and incident electric field, respectively. The subscripts 1 and 2 refer to any two general orthogonal polarizations (here H $\hat{=}$ 1 and V $\hat{=}$ 2)

In vector notation, equation (1.10.1) can be written as:

$$\underline{E}_s = \frac{\exp(-j k_0 r)}{r} [S] \underline{E}_i \quad (1.10.2)$$

Assuming that the propagation space is reciprocal, one can now represent the scattering matrix in terms of amplitudes and phases where for a monostatic radar the relative scattering matrix becomes symmetric and is given by:

$$[S]_{SMR} = \begin{bmatrix} |S_{11}|e^{j(\phi_{11} - \phi_{12})} & |S_{12}| \\ |S_{21}| & |S_{22}|e^{j(\phi_{22} - \phi_{12})} \end{bmatrix} \quad (1.10.3)$$

where the $| \ |$ brackets denote absolute value.

For the monostatic reciprocal radar case, it can be shown from the Reciprocity Theorem that $|S_{21}| = |S_{12}|$ and $\phi_{21} = \phi_{12}$. Throughout the remaining discussion, it will be assumed the $[S]$ implies the monostatic reciprocal, relative phase $[S]_{SMR}$ case unless specifically stated otherwise.

The radar cross section of a target is related to the scattering matrix by:

$$\sigma_{ij} = |S_{ij}|^2 \quad (1.10.4)$$

where $i, j = 1$ or 2

The radar cross section of a random array of objects (such as precipitation particles) fluctuates with pulse and range time. The fluctuations are not caused by changes in the radar cross sections of the individual objects; but rather they are due almost entirely to phase effects. Each object in the contributing region gives rise to a scattered wavelet with a certain phase, and the total scattered electric field is the sum of the interference effects of the individual wavelets. Since the relative phases of the wavelets change as the objects move about during the interval between radar pulses, the total echo power varies with time. The relative phases also vary with time in a random fashion, so the fluctuations are called "random phase" fluctuations. The amplitudes of the wavelets (or equivalently, the random cross sections of individual objects) sometimes vary as well. However, any echo fluctuations due to such amplitude changes will be superimposed or masked out by the "random phase" fluctuations.

Random-phase fluctuations are a characteristic feature of precipitation echoes. Because of the random-phase fluctuations, the radar cross-section for a distributed target can be expressed as:

$$\bar{\sigma}_{ij} = \overline{|S_{ij}|^2} \quad (1.10.5)$$

where $i, j = 1$ or 2 and the bar above the elements denote averaging for an ensemble of particles within the radar pulse.

Random-phase fluctuations also occur in "range-time" as the contributing region moves out from the radar; thus, the contributing region contains a different set of hydrometeors each time it moves out by its own length. Fluctuations of a similar nature can also occur as the antenna is rotated because the contributing region moves with the antenna beam.

The echo power $[P_R]$ received from a contributing region at range r on any one radar pulse is not in general equal to the average power $\langle [P_R] \rangle$ because of the random phase fluctuations. Thus, the power, $[P_R]$, may be higher or lower than $\langle [P_R] \rangle$ by an amount that can only be predicted statistically.

Measuring the average echo power $\langle [P_R] \rangle$ from any contributing region exactly would require averaging over an infinite time interval. In practice, however, it is therefore necessary to estimate the average echo power $\langle [P_R] \rangle$ by observing only a limited number of echoes from each contributing region.

From Figure 1.14, the following equation for the ensemble average radar cross-section is:

$$\bar{\sigma} = \sum_{i=1}^N \overline{|S_i|^2} \exp \left[\frac{-4\pi r_i}{\lambda} \right] \quad (1.10.6)$$

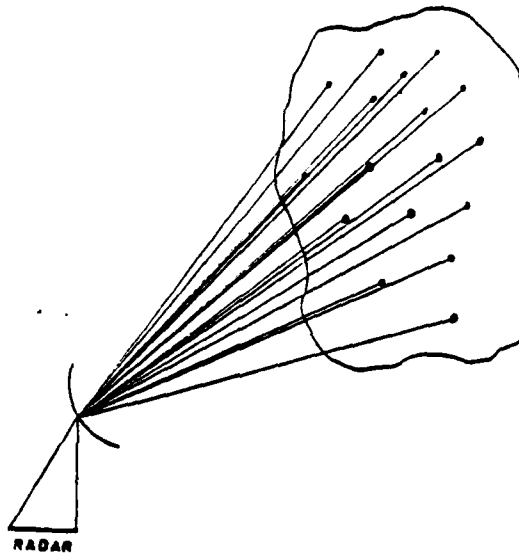


FIGURE 1.14: AMPLITUDE STATISTICS OF THE RADAR CROSS SECTION

Thus, by the Central Limit Theorem which states that the mean of N samples follows a Gaussian distribution whatever the distribution of the individual measurements, it can then be assumed that the scattering matrix elements are zero-mean Gaussian and statistically independent when N is large. Consequently, the radar cross-section is Rayleigh distributed, because it is the product of two Gaussian distributions. It can be seen that the above assumptions are in total agreement with the earlier work of Marshall and Hirschfeld (1953).

1.10.3 Transformations to Circular and Elliptical Polarizations

No stipulation has been made about a specific polarization basis thus far in this section. Up to this point, the only requirement has been that the transmitted polarizations be orthogonal. Through the appropriate congruent transformations, it has been shown (Crispin and Siegal 1969) that the linear scattering matrix $[LSM] = [S]_L$, can be transformed to a circular scattering matrix $[CSM] = [S]_C$, or, in general, to an elliptical scattering matrix $[ESM] = [S]_E$.

To transform $[S]$ to different polarization states, the following matrix

transformation can be used:

$$[S']_i = [T][S][T]^T \quad (1.10.7)$$

where the subscript $i \rightarrow l$ represents the scattering matrix in a linear polarization basis where l is usually implied when no subscript is present. For the scattering matrix in circular or elliptical polarizations, $i \rightarrow c$ or e , respectively. The superscript T denotes the transpose of the transformation matrix $[T]$.

The most general form of $[T]$ can be found to be:

$$[T] = \begin{bmatrix} e^{j\phi_1} \cos\beta & -e^{j\phi_2} \sin\beta \\ e^{j\phi_3} \sin\beta & e^{j\phi_4} \cos\beta \end{bmatrix} \quad (1.10.8)$$

where $\phi_2 - \phi_1 = \phi_4 - \phi_3$. It should be noted that the most general basis is elliptic; but when all the phases are set to zero, $[T]$ reduces to an ordinary rotational matrix which rotates a particular linear polarization base by an angle β . There exist numerous transformation matrices for transforming between unit vectors of any polarization basis depending on one's choice of $\phi_1, \phi_2, \phi_3, \phi_4$ and β .

In this work, the transformation matrix will be taken as:

$$[T] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ 1 & +j \end{bmatrix} \quad (1.10.9)$$

to transform between the linear and the circular scattering matrix. Hence, from equation (1.10.7)

$$[S]_c = \frac{1}{2} \begin{bmatrix} 1 & -j \\ 1 & +j \end{bmatrix} \cdot \begin{bmatrix} S_{11} & S_{12} \\ S_{12} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 \\ -j & +j \end{bmatrix} \quad (1.10.10)$$

Finally, the scattering matrix in circular coordinates becomes:

$$[S]_c = \frac{1}{2} \begin{bmatrix} S_{11} - S_{22} - j2S_{12} & S_{11} + S_{22} \\ S_{11} + S_{22} & S_{11} - S_{22} + j2S_{12} \end{bmatrix} \quad (1.10.11)$$

The transformation given in equation (1.10.8) is necessary if the non-ideal nature of the radar antenna is to be taken into account. Whether one desires to use linear or circular polarizations, in practice, the received polarizations will be elliptical. For any practical analysis of a dual-polarizations systems, antenna effects should be included by using the rotational and elliptical transformations presented above.

1.10.4 The Backscattered Coherency Matrix

For a radar volume filled with scatterers, the received power is due to the backscattered component of all N scatterers within the radar volume. Thus, equation (1.10.1) for partially polarized signals can be represented using the coherency matrix $[J]$.

$$[J]_s = \langle \underline{E}_s \underline{E}_s^* \rangle = \begin{bmatrix} \langle E_{s1} E_{s1}^* \rangle & \langle E_{s1} E_{s2}^* \rangle \\ \langle E_{s2} E_{s1}^* \rangle & \langle E_{s2} E_{s2}^* \rangle \end{bmatrix} \quad (1.10.12)$$

$$= \langle \frac{1}{r^2} [S] \underline{E}_i \underline{E}_i^* [S]^* \rangle \quad (1.10.13)$$

where $*$ and T denote the complex conjugate and transpose, respectively and the subscripts s and i denote the scattered and incident coherency matrix, respectively.

Expanding the above equation (1.10.13) yields:

$$\begin{aligned} J_{s11} &= \langle S_{11} [S_{11}^* |E_{i1}|^2 + S_{12}^* E_{i1} E_{i2}^*] + S_{12} [S_{11}^* E_{i2} E_{i1}^* + \\ &\quad S_{12}^* |E_{i2}|^2] \rangle \\ J_{s12} &= \langle S_{11} [S_{21}^* |E_{i1}|^2 + S_{22}^* E_{i1} E_{i2}^*] + S_{21} [S_{21}^* E_{i2} E_{i1}^* + \\ &\quad S_{22}^* |E_{i2}|^2] \rangle \end{aligned} \quad (1.10.14)$$

$$\begin{aligned} J_{s21} &= \langle S_{22} [S_{12}^* |E_{i2}|^2 + S_{11}^* E_{i2} E_{i1}^*] + S_{21} [S_{12}^* E_{i1} E_{i2}^* + \\ &\quad S_{11}^* |E_{i1}|^2] \rangle \end{aligned}$$

$$\begin{aligned} J_{s22} &= \langle S_{22} [S_{22}^* |E_{i2}|^2 + S_{21}^* E_{i2} E_{i1}^*] + S_{21} [S_{22}^* E_{i1} E_{i2}^* + \\ &\quad S_{21}^* |E_{i1}|^2] \rangle \end{aligned}$$

Recalling from Section 1.10.1, that $S_{21} = S_{12}$ for a monostatic radar, the

above equation (1.10.14) can be simplified to:

$$J_{s11} = \langle |S_{11}|^2 |E_{i1}|^2 + 2\text{Re}[S_{11}S_{12}^* E_{i1}E_{i2}^*] + |S_{12}|^2 |E_{i2}|^2 \rangle$$

$$J_{s12} = \langle S_{11}S_{12}^* |E_{i1}|^2 + S_{11}S_{22}^* E_{i1}E_{i2}^* + |S_{12}|^2 E_{i2}E_{i1}^* + S_{22}S_{12}^* |E_{i2}|^2 \rangle \quad (1.10.15)$$

$$J_{s21} = J_{s12}^*$$

$$J_{s22} = \langle |S_{22}|^2 |E_{i2}|^2 + 2\text{Re}[S_{22}S_{12}^* E_{i2}E_{i1}^*] + |S_{12}|^2 |E_{i1}|^2 \rangle$$

1.10.5 The Relationship Between The Average Mueller Matrix, the Coherency Matrix, and the Scattering Matrix

Up to this point, the polarization properties of distributed targets such as precipitation have been represented in terms of the incident and scattered coherency matrix and the 2x2 scattering matrix. The coherency matrix elements can be represented in terms of the 4x1 Stokes vector; an alternative representation is:

$$\underline{g}_s = [M]\underline{g}_i \quad (1.10.16)$$

where \underline{g}_s and \underline{g}_i are the scattered and incident waves expressed as Stokes vectors and $[M]$ is the 4x4 real and symmetric average Mueller matrix used to represent partially polarized signals. It has been shown by Chan (1981) that a transformation exists between the scattering matrix $[S]$ and the Mueller matrix $[M]$. Equation (1.10.16) can then be expressed as:

$$\begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix}_s = \begin{bmatrix} \bar{m}_{11} & \bar{m}_{12} & \bar{m}_{13} & \bar{m}_{14} \\ \bar{m}_{21} & \bar{m}_{22} & \bar{m}_{23} & \bar{m}_{24} \\ \bar{m}_{31} & \bar{m}_{32} & \bar{m}_{33} & \bar{m}_{34} \\ \bar{m}_{41} & \bar{m}_{42} & \bar{m}_{43} & \bar{m}_{44} \end{bmatrix} \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix}_i \quad (1.10.17)$$

The Stokes parameters and the elements of the coherency matrix are related by:

$$g_0 = J_{11} + J_{22}$$

$$g_1 = J_{11} - J_{22}$$

$$g_2 = J_{12} + J_{21}$$

$$g_3 = j(J_{12} - J_{21})$$

where $j = -1$.

The following expressions relate the scattered Stokes elements to the incident coherency matrix elements and the scattering matrix elements by substituting equations (1.10.15) into the above equation, yielding:

$$\begin{aligned}
 g_{s0} &= \langle |S_{11}|^2 |E_{11}|^2 + 2\text{Re}[S_{11}S_{12}^* E_{11}E_{12}^*] + |S_{12}|^2 |E_{12}|^2 \rangle \\
 &\quad + \langle |S_{22}|^2 |E_{12}|^2 + 2\text{Re}[S_{22}S_{12}^* E_{12}E_{11}^*] + |S_{12}|^2 |E_{11}|^2 \rangle \\
 g_{s1} &= \langle |S_{11}|^2 |E_{11}|^2 + 2\text{Re}[S_{11}S_{12}^* E_{11}E_{12}^*] + |S_{12}|^2 |E_{12}|^2 \rangle \\
 &\quad - \langle |S_{22}|^2 |E_{12}|^2 + 2\text{Re}[S_{22}S_{12}^* E_{12}E_{11}^*] + |S_{12}|^2 |E_{11}|^2 \rangle \\
 g_{s2} &= \langle S_{11}S_{12}^* |E_{11}|^2 + S_{11}S_{22}^* E_{11}E_{12}^* + |S_{12}|^2 E_{12}E_{11}^* \\
 &\quad + S_{22}S_{12}^* |E_{12}|^2 + \langle S_{11}^* S_{22} E_{12}E_{11}^* + |S_{12}|^2 E_{11}E_{12}^* \\
 &\quad + S_{22}^* S_{12} |E_{12}|^2 + S_{11}^* S_{12} |E_{11}|^2 \rangle \\
 g_{s3} &= \langle j[S_{11}S_{12}^* |E_{11}|^2 + S_{11}S_{22}^* E_{11}E_{12}^* + |S_{12}|^2 E_{12}E_{11}^* \\
 &\quad + S_{22}S_{12}^* |E_{12}|^2] - \langle j[S_{11}^* S_{12} |E_{11}|^2 + S_{11}^* S_{22} E_{12}^* E_{11}^* \\
 &\quad + |S_{12}|^2 E_{11}E_{12}^* + S_{22}S_{12}^* |E_{12}|^2] \rangle
 \end{aligned} \tag{1.10.18}$$

At this point, it should be noted that, when polarization '1' is transmitted and both '1' and orthogonal '2' are received the scattered Stokes parameters become:

$$\begin{aligned}
 g_{s0} &= \langle |S_{11}|^2 |E_{11}|^2 \rangle + \langle |S_{12}|^2 |E_{11}|^2 \rangle \\
 g_{s1} &= \langle |S_{11}|^2 |E_{11}|^2 \rangle - \langle |S_{12}|^2 |E_{11}|^2 \rangle \\
 g_{s2} &= \langle S_{11}S_{12} |E_{11}|^2 \rangle + \langle S_{11}S_{22}^* |E_{11}|^2 \rangle \\
 g_{s3} &= \langle j[S_{11}S_{12}^* |E_{11}|^2] \rangle - \langle j[S_{11}^* S_{12} |E_{11}|^2] \rangle
 \end{aligned} \tag{1.10.19}$$

Similarly, when orthogonal polarization '2' is transmitted and both co-po-

larized '2' and cross-polarized '1' are received, the scattered Stokes parameters become:

$$\begin{aligned}
 g_{s0} &= \langle |S_{12}|^2 |E_{12}|^2 \rangle + \langle |S_{22}|^2 |E_{12}|^2 \rangle \\
 g_{s1} &= \langle |S_{12}|^2 |E_{12}|^2 \rangle - \langle |S_{22}|^2 |E_{12}|^2 \rangle \\
 g_{s2} &= \langle S_{22} S_{12} |E_{12}|^2 \rangle + \langle S_{22} S_{12}^* |E_{12}|^2 \rangle \\
 g_{s3} &= \langle j[S_{22} S_{12} |E_{12}|^2] \rangle - \langle j[S_{22}^* S_{12} |E_{12}|^2] \rangle
 \end{aligned}
 \tag{1.10.20}$$

In general, the 4x4 symmetric average Mueller matrix $[M]$ can be expressed as:

$$[G]_s [G]_i^{-1} = [M] \tag{1.10.21}$$

where

$$[G]_s = \begin{pmatrix} g_{s0} \\ g_{s1} \\ g_{s2} \\ g_{s3} \end{pmatrix} \tag{1.10.22}$$

$[G]_s$ can be expressed in terms of the scattering matrix elements and the incident electric fields by substituting equations (1.10.18) into (1.10.22) yielding:

$$[G]_s = \begin{pmatrix} \langle |S_{11}|^2 |E_{11}|^2 + 2\text{Re}[S_{11} S_{12}^* E_{11} E_{12}^*] + |S_{12}|^2 |E_{12}|^2 \rangle \\ + \langle |S_{22}|^2 |E_{12}|^2 + 2\text{Re}[S_{22} S_{12}^* E_{12} E_{11}^*] + |S_{12}|^2 |E_{11}|^2 \rangle \\ \langle |S_{11}|^2 |E_{11}|^2 + 2\text{Re}[S_{11} S_{12}^* E_{11} E_{12}^*] + |S_{12}|^2 |E_{12}|^2 \rangle \\ - \langle |S_{22}|^2 |E_{12}|^2 + 2\text{Re}[S_{22} S_{12}^* E_{12} E_{11}^*] + |S_{12}|^2 |E_{11}|^2 \rangle \\ \langle S_{11} S_{12}^* |E_{11}|^2 + S_{11} S_{22}^* E_{11} E_{12}^* + |S_{12}|^2 E_{12} E_{11}^* \rangle \end{pmatrix} \tag{1.10.23}$$

$$\begin{aligned}
 & + \langle S_{22} S_{12}^* |E_{i2}|^2 \rangle + \langle S_{11}^* S_{22} E_{i2} E_{i1}^* + |S_{12}|^2 E_{i1} E_{i2}^* \\
 & + S_{22}^* S_{12} |E_{i2}|^2 + S_{11}^* S_{12} |E_{i1}|^2 \rangle \\
 & \langle j[S_{11} S_{12}^* |E_{i1}|^2 + S_{11} S_{22}^* E_{i1} E_{i2}^* + |S_{12}|^2 E_{i2} E_{i1}^* \\
 & + S_{22} S_{12}^* |E_{i2}|^2] \rangle - \langle j[S_{11}^* S_{12} |E_{i1}|^2 + S_{11}^* S_{22} E_{i2}^* E_{i1}^* \\
 & + |S_{12}|^2 E_{i1} E_{i2}^* + S_{22} S_{12}^* |E_{i2}|^2] \rangle
 \end{aligned}$$

$[G]_s$ for polarization 1 becomes:

$$[G]_{s1} = \begin{bmatrix} \langle |S_{11}|^2 |E_{i1}|^2 \rangle + \langle |S_{12}|^2 |E_{i1}|^2 \rangle \\ \langle |S_{11}|^2 |E_{i1}|^2 \rangle - \langle |S_{12}|^2 |E_{i1}|^2 \rangle \\ \langle S_{11} S_{12}^* |E_{i1}|^2 \rangle + \langle S_{11}^* S_{22} |E_{i1}|^2 \rangle \\ \langle j[S_{11} S_{12}^* |E_{i1}|^2] \rangle - \langle j[S_{11}^* S_{12} |E_{i1}|^2] \rangle \end{bmatrix} \quad (1.10.24)$$

Similarly, $[G]_s$ in polarization 2 becomes:

$$[G]_{s2} = \begin{bmatrix} \langle |S_{12}|^2 |E_{i2}|^2 \rangle + \langle |S_{22}|^2 |E_{i2}|^2 \rangle \\ \langle |S_{12}|^2 |E_{i2}|^2 \rangle - \langle |S_{22}|^2 |E_{i2}|^2 \rangle \\ \langle S_{22} S_{12} |E_{i2}|^2 \rangle + \langle S_{22} S_{12}^* |E_{i2}|^2 \rangle \\ \langle j[S_{22} S_{12} |E_{i2}|^2] \rangle - \langle j[S_{22}^* S_{12} |E_{i2}|^2] \rangle \end{bmatrix} \quad (1.10.25)$$

Finally, it should be noted that $[G]_i$ can be expressed in terms of the incident coherency matrix as:

$$[G]_i = \begin{bmatrix} g_{i0} \\ g_{i1} \\ g_{i2} \\ g_{i3} \end{bmatrix} = \begin{bmatrix} J_{i11} + J_{i22} \\ J_{i11} - J_{i22} \\ J_{i12} + J_{i21} \\ j(J_{i12} - J_{i21}) \end{bmatrix} \quad (1.10.26)$$

1.10.6 Optimal Polarization Concept for Dual Polarization Radar

For any precipitation medium, it is well known that there exists at least one minimum and maximum polarization pair. These are the polarizations where minimum and maximum voltages are received across the antenna terminals of a radar. They are also known as the optimal polarizations (co and cross-pol nulls) and are those two polarizations which when transmitted produce minimum and maximum voltages, respectively, upon reception.

In order to obtain all of the backscatter properties of an assembly of scatterers, it is necessary to make a complete measurement of the polarization, amplitude and relative phase characteristics of the backscattered signal. This can be done, for example, by means of measuring either the Stokes parameters or the coherency matrix. The two methods have been seen to be equivalent in the previous section. Such measurements for a dual polarization radar require two separate sequential orthogonal transmissions, the polarizations of which determine the base vectors for the measurement. Part of the information contained in this system of measurements can also be obtained from a knowledge of the two optimal polarizations, say one co-pol and one cross-pol null. Optimal polarizations do not in themselves constitute a complete backscatter description, but they can be made complete by a measurement of the cross-section and the degree of polarization. Alternatively, the measurement can be completed by obtaining the power in the co-pol channel and the orthogonal channel (McCormick 1982).

The latter alternative suggests the possibility of a new complete measurement system in which optimal polarizations and the related channel levels are obtained experimentally. But this presumably would imply a scanning technique in azimuth and/or elevation which does not appear attractive because of the accompanying loss in angular resolution in the resulting data, as well as, suffering from the disadvantage that the data rate is determined by the stochastic nature of the target which may well have undergone macroscopic changes before the scanning cycle is complete.

Consider a coherent dual-polarization radar that has the capability of polarization adaptivity and which can also recover the scattering matrix below the decorrelation or "reshuffling" time of hydrometeors. The decorrelation time, T_r , can be thought of as the rearrangement of particles with respect to each other in phase space. If the polarization switching taken on successive pulses is accomplished below T_r , (i.e., the decorrelation time in phase space), then observations taken between successive pulse are independent, and the particles can be considered stationary. Thus, the received signals can also be considered completely polarized. If, however, the switching cannot be done below the decorrelation time of the particles, then the pulses are not independent, and the particles are considered non-stationary. Consequently, the received signals are partially polarized. Typically, the time required to attain independence (i.e., decorrelation time for successive pulses) is of the order of the time required for the relative positions of the particles to change by one-half the radar wavelength.

1.10.6.1 Optimal Polarizations for Completely Polarized Signals

With fast (under the decorrelation time of hydrometeors) polarization switching, the co and cross pol nulls will then be calculated instead of employing a measurement technique in this section under the assumption that the received signals are completely polarized. The most general form of the transformation matrix was given in equation (1.10.8). Making the appropriate substitutions will yield:

$$[T] = \begin{bmatrix} \cos \frac{\gamma}{2} & -e^{j\alpha} \sin \frac{\gamma}{2} \\ e^{-j\alpha} \sin \frac{\gamma}{2} & \cos \frac{\gamma}{2} \end{bmatrix} \quad (1.10.27)$$

$$\text{where } \phi_1 = \phi_4 = 0$$

$$\phi_2 = -\phi_3 = \alpha$$

$$\beta = \gamma/2$$

It should be noted that the transformation matrix $[T]$ is unitary as well.

It is convenient to rearrange equation (1.10.27) as:

$$[T] = \frac{1}{(1+\rho\rho^*)^{1/2}} \begin{bmatrix} 1 & -\rho \\ \rho^* & 1 \end{bmatrix} \quad (1.10.28)$$

$$\text{where } \rho = e^{j\alpha} \tan \gamma/2.$$

Recalling from equation (1.10.2) that the incident electric field was represented in matrix notation by \underline{E}_i , and the scattered electric field by \underline{E}_s ;

then the transformations of the electric field to the new optimal basis are given by:

$$\underline{E}'_i = [T] \underline{E}_i \quad (1.10.29)$$

$$\underline{E}'_s = [T^*] \underline{E}_s \quad (1.10.30)$$

where the prime denotes the new change of basis and the * denotes the complex conjugate.

When equations (1.10.29) and (1.10.30) are substituted into equation (1.10.1), the electric fields can be expressed in the new optimal basis as:

$$\begin{bmatrix} E'_{s1} \\ E'_{s2} \end{bmatrix} = \frac{\exp(-jk_0 r)}{r} [T^*] \begin{bmatrix} S_{11} & S_{12} \\ S_{12} & S_{22} \end{bmatrix} [T^*]^T \begin{bmatrix} E'_{i1} \\ E'_{i2} \end{bmatrix} \quad (1.10.31)$$

Alternatively, in matrix notation equation (1.10.31) becomes:

$$\underline{E}'_s = \frac{\exp(-jk_0 r)}{r} [S'] \underline{E}'_i \quad (1.10.32)$$

where $[S'] = [T^*][S][T^*]^T \quad (1.10.33)$

and is the scattering matrix in the optimal polarization base.

Expanding equation (1.10.33), the elements of $[S']$ become:

$$S'_{11} = (1 + \rho\rho^*)^{-1} (\rho^2 S_{22} + 2\rho S_{12} + S_{11}) \quad (1.10.34a)$$

$$S'_{12} = (1 + \rho\rho^*)^{-1} (\rho^2 S_{22} + (1 - \rho\rho^*)S_{12} - \rho^* S_{11}) \quad (1.10.34b)$$

$$S'_{21} = S'_{12} \quad (1.10.34c)$$

$$S'_{22} = (1 + \rho\rho^*)^{-1} (\rho^* S_{11} - 2\rho^* S_{12} + S_{22}) \quad (1.10.34d)$$

Expressions for the co and cross pol nulls can be calculated by assuming the first normalized sequential pulse (polarization 1) transmitted in equation (1.10.31) is given by:

$$\begin{bmatrix} E'_{s1} \\ E'_{s2} \end{bmatrix} = \frac{\exp(-jk_0 r)}{r} \cdot [S'] \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Setting $E'_{s1} = 0$ in equation (1.10.31) yields the following expression for the co-pol nulls:

$$\rho_{1co} = \frac{-S_{12} \pm (S_{12}^2 - S_{11}S_{22})^{1/2}}{S_{22}} \quad (1.10.35)$$

Setting $E'_{s2} = 0$ in equation (1.10.31) yields the following expression for the cross-pol nulls:

$$\rho_{1x} = \frac{-B \pm (B^2 - 4AC)^{1/2}}{2A} \quad (1.10.36)$$

where

$$\begin{aligned} A &= S_{22}S_{12}^* + S_{11}^*S_{12} \\ B &= |S_{11}|^2 - |S_{22}|^2 \\ C &= -A^* \end{aligned}$$

Alternatively, one can obtain expressions for the co and cross-pol nulls in polarization 2 by assuming that the normalized second sequential pulse transmitted is:

$$\begin{bmatrix} E'_{s1} \\ E'_{s2} \end{bmatrix} = \frac{\exp(-jk_0 r)}{r} \cdot [S'] \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (1.10.37)$$

1.10.7 Optimal Polarizations for Completely Polarized Signals and their Relationship to the Elliptical Depolarization Ratio

In general, the backscattered signal from an ensemble of hydrometeors will be elliptically polarized, and it may be desirable for an adaptive dual-polarization radar to receive in an elliptical mode. An elliptical depolarization ratio (EDR) may be defined where CDR is just a special case.

Recalling that the scattering matrix in an transformed elliptical polarization base can be expressed as:

$$[S']_e = \begin{bmatrix} S'_{e11} & S'_{e12} \\ S'_{e12} & S'_{e22} \end{bmatrix} \quad (1.10.38)$$

or

$$[S']_e = S'_{e12} \begin{bmatrix} \eta'_{e11} & 1 \\ 1 & \eta'_{e22} \end{bmatrix} \quad (1.10.39)$$

Following the same procedure as in the previous section, optimal polarizations can be expressed in terms of the non-logarithmic parameter used to calculate EDR as:

$$\rho_{1co} = \frac{-1 \pm \sqrt{1 - \eta_{e11} \eta_{e22}}}{\eta_{e11}} \quad (1.10.40)$$

$$\rho_{1x} = \frac{1}{2} \frac{|\eta_{e11}|^2 - |\eta_{e22}|^2}{|\eta_{e11} + \eta_{e22}|} \pm \sqrt{1 + \frac{(|\eta_{e11}|^2 - |\eta_{e22}|^2)^2}{4|\eta_{e11} + \eta_{e22}|^2}} \quad (1.10.41)$$

1.10.8 Optimal Polarizations for Partially Polarized Signals

When polarization switching cannot be accomplished below the decorrelation time of hydrometeors, the particles within the radar volume are considered non-stationary; resulting in the received signals being partially polarized. Thus, expressions for the optimal polarizations will be developed in this section under the assumption that the polarization switching for a dual polarization radar is above the decorrelation time of hydrometeors.

Recalling that the scattering matrix elements in an optimal polarization base are given in equation (1.10.34 a-d) as:

$$\begin{aligned} S'_{11} &= (1 + \rho\rho^*) (\rho^2 S_{22} + 2\rho S_{12} + S_{11}) \\ S'_{12} &= (1 + \rho\rho^*)^{-1} (\rho S_{22} + (1 - \rho\rho^*) S_{12} - \rho^* S_{11}) \\ S'_{21} &= S'_{12} \\ S'_{22} &= (1 + \rho\rho^*) (\rho^* S_{11} - 2\rho^* S_{12} + S_{22}). \end{aligned}$$

The backscattered coherency matrix can now be expressed in terms of the optimal scattering matrix elements. When polarization 1 is transmitted, the backscattered coherency matrix elements in the optimal polarization base simplify

$$\begin{aligned} J'_{s11} &= \langle |S'_{11}|^2 |E'_{i1}|^2 \rangle \\ J'_{s12} &= \langle S'_{11} S'_{12}^* |E'_{i1}|^2 \rangle \\ J'_{s21} &= J'_{s12} \\ J'_{s22} &= \langle |S'_{12}|^2 |E'_{i1}|^2 \rangle \end{aligned} \tag{1.10.42}$$

For either J'_{s11} or J'_{s12} a minimum, the optimal polarizations can be seen to be formally the same as for the completely polarized case presented (Nespor 1983) with S'_{11} , S'_{12} and S'_{22} being replaced by their ensemble averages:

$$\rho_{1co} = \frac{-\overline{S'_{12}} \pm \sqrt{\overline{S'_{12}}^2 - \overline{S'_{11}} \overline{S'_{22}}}}{\overline{S'_{22}}} \tag{1.10.43}$$

$$\rho_{1x} = \frac{-\overline{B} \pm \sqrt{\overline{B}^2 - 4\overline{A} \overline{C}}}{2\overline{A}} \tag{1.10.44}$$

where $\overline{A} = \overline{S'_{22} S'_{12}^*} + \overline{S'_{11} S'_{12}}$

$$\overline{B} = |\overline{S'_{11}}|^2 - |\overline{S'_{22}}|^2$$

$$\overline{C} = \overline{S'_{11} S'_{12}^*} - \overline{S'_{22}^* S'_{12}}$$

where the bar denotes ensemble averaging.

Similarly, expressions for the optimal polarizations can be obtained for polarization 2, as shown in Nespor (1983).

1.10.9 Optimal Polarizations for Partially Polarized Signals and their Relationship to the Elliptical Depolarization Ratio

It can be seen that the optimal polarizations for partially polarized signals in terms of the non-logarithmic parameter used to calculate EDR for polarizations 1 and 2 are:

$$\rho_{1co} = \frac{-1 \pm \sqrt{1 - \bar{\eta}_{e11} \bar{\eta}_{e22}}}{\bar{\eta}_{e11}} \quad (1.10.45)$$

$$\rho_{1x} = \frac{1}{2} \frac{|\bar{\eta}'_{e11}|^2 - |\bar{\eta}'_{e22}|^2}{|\bar{\eta}'_{e11} + \bar{\eta}'_{e22}|^2} \pm \sqrt{1 + \frac{(|\bar{\eta}'_{e11}|^2 - |\bar{\eta}'_{e22}|^2)^2}{4 |\bar{\eta}'_{e11} + \bar{\eta}'_{e22}|^2}} \quad (1.10.46)$$

1.10.10 The Degree of Polarization

The degree of polarization, P, was defined as the ratio of the intensity of the polarized portion of the wave to the total intensity of the wave and was given by:

$$P = \sqrt{1 - \frac{4 \det[J]}{(\text{Tr}[J])^2}}$$

When polarization 1 is transmitted, the $\det[J'_s]$ and $\text{Tr}[J'_s]$ can be calculated from equation (1.10.42) as:

$$\begin{aligned} \det[J'_s] = & \langle |S'_{11}|^2 |E'_{i1}|^2 \rangle \langle |S'_{12}|^2 |E'_{i1}|^2 \rangle \\ & - \langle S'_{11} S'_{12}^* |E'_{i1}|^2 \rangle \langle S'_{11}^* S'_{12} |E'_{i1}|^2 \rangle \end{aligned} \quad (1.10.47)$$

$$\text{Tr}[J'_s] = \langle |S'_{11}|^2 |E'_{i1}|^2 \rangle + \langle |S'_{12}|^2 |E'_{i1}|^2 \rangle \quad (1.10.48)$$

The degree of polarization, therefore, for polarization 1 is obtained by substituting equations (1.10.47) and (1.10.48) into the above expression for P, yielding:

$$P_1 = \sqrt{1 - \frac{4[|\bar{S}'_{11}|^2 |\bar{S}'_{12}|^2 - |\bar{S}'_{11} \bar{S}'_{12}|^2]}{(|\bar{S}'_{11}|^2 + |\bar{S}'_{12}|^2)^2}} \quad (1.10.49)$$

where the bar denotes averaging.

Similarly, P_2 can be found to be:

$$P_2 = \sqrt{1 - \frac{4[|\bar{S}'_{22}|^2 |\bar{S}'_{12}|^2 - |\bar{S}'_{22} \bar{S}'_{12}|^2]}{(|\bar{S}'_{22}|^2 + |\bar{S}'_{12}|^2)^2}} \quad (1.10.50)$$

1.10.11 The Degree of Coherence (Orientation)

The degree of coherence, μ , was seen to be the complex correlation factor between intensities.

Where μ was given as:

$$\mu = \frac{J_{12}}{\sqrt{J_{11}J_{22}}}$$

Thus, when polarization 1 is transmitted the degree of coherence is given by:

$$\mu_1 = \frac{\overline{S'_{11} S'_{12}^*}}{[\overline{S'_{11} S'_{11}}]^{1/2} \cdot [\overline{S'_{12} S'_{12}}]^{1/2}} \quad (1.10.51)$$

Similarly, when polarization 2 is transmitted, the degree of coherence becomes:

$$\mu_2 = \frac{\overline{S'_{22} S'_{12}^*}}{[\overline{S'_{12} S'_{12}}]^{1/2} \cdot [\overline{S'_{22} S'_{22}}]^{1/2}} \quad (1.10.52)$$

1.10.12 The Poincaré Polarization Sphere

The Poincaré Sphere is a valuable graphical aid which maps each polarization state of a received signal to a unique point on the surface of the sphere. In Figure 1.15 the Poincaré Sphere along with some of its unique properties is presented.

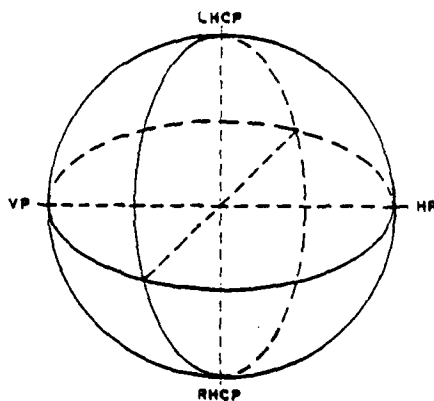


FIGURE 1.15: THE POINCARÉ SPHERE

When the received signal is represented by ρ , its corresponding spherical coordinates on the sphere are obtained by the introduction of an auxiliary complex parameter u :

$$\text{where } u = \frac{1 - j\rho}{1 + j\rho} \quad (1.10.53)$$

The coordinates on the sphere are given by:

$$\text{radius: } r = 1$$

$$\text{co-latitude: } \theta = \cos^{-1} \left(\frac{|u|^2 - 1}{|u|^2 + 1} \right)$$

$$\text{longitude: } \phi = \arg(u) = \tan^{-1} \left(\frac{\text{Im}(u)}{\text{Re}(u)} \right)$$

From Figure 1.15, some of the important properties of the Poincaré Sphere are summarized:

- (1) Points on the upper hemisphere represent left-handed polarizations, and conversely, points on the lower hemisphere represent right-handed polarizations.
- (2) The poles represent circular polarizations.
- (3) All points on the equator represent linear polarizations with horizontal at zero latitude and zero longitude.
- (4) Orthogonal polarizations are antipodal.
- (5) All points along a given latitude circle represent the same ellipticity or axis ratio.
- (6) All points along a given longitude represent the same orientation angle with 0° orientation along the zero meridian and 90° tilt along the 180° meridian.

For ensembles of hydrometeors, the optimal polarizations will distribute themselves on the sphere from fluctuations due to the motion of scatterers as discussed in Section 1.10.1. This distribution of optimal polarizations represented on the Poincaré Sphere along with the mean and spread given in Section 1.10.13 is demonstrated in Figure 1.16.

The polarization chart given in Figure 1.17 is capable of representing all polarization states and in effect, maps the surface of the Poincaré Sphere onto a circle. More precisely, the polarization chart is an orthogonal projection of the Poincaré Sphere on a plane, having polar coordinates $\rho = \cos(2\tau)$ and $\psi = 2\phi$ where τ is the ellipticity angle and ϕ is the orientation angle of the polarization ellipse. The modified polarization chart has as polar coordinates $\rho = 1 - |r|$ where $r = \tan \tau$ and $\psi = 2\phi$. For $-1 < r < 0$ represents right-handed elliptical (RHEP), $r = 0$ linear polarizations and $0 < r < 1$ left-handed elliptical polarization (LHEP).

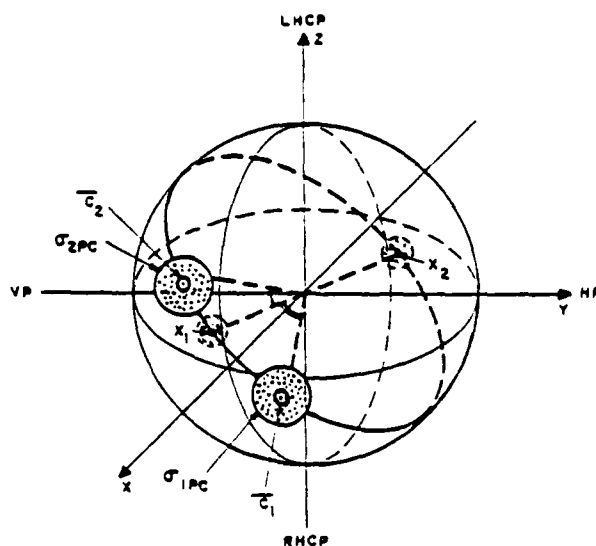


FIGURE 1.16: THEORETICAL REPRESENTATION OF OPTIMAL POLARIZATION ON THE POINCARÉ SPHERE

Examples of plots for hydrometeor ensembles on the polarization chart are given in Figures 1.18 and 1.19. In Figure 1.18, Rosien et. al. (1979) have plotted the polarization states of signals backscattered from a random dipole cloud for three different antenna polarizations transmitted in vertical, horizontal and circular polarizations. Data for these plots were obtained from a simulated model for dipoles oriented primarily within 30° from the horizontal. In this example, left-handed polarizations are arbitrarily mapped onto the lower half of the vertical axis and the right-handed elliptical polarizations onto the upper half of the vertical axis. Also, the size of the letter used for indicating the polarization of the received signal is varied in accordance with the total signal power in the wave, i.e., maximum power that can be extracted from the wave by the matched antenna.

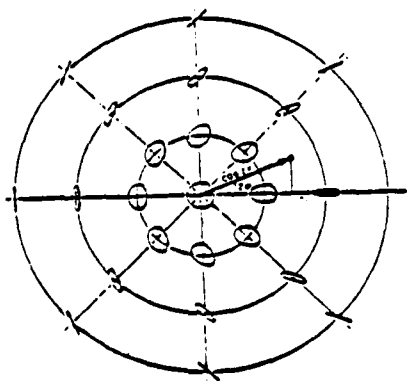


FIGURE 1.17: THE POLARIZATION CHART
HUYNEN (1970)

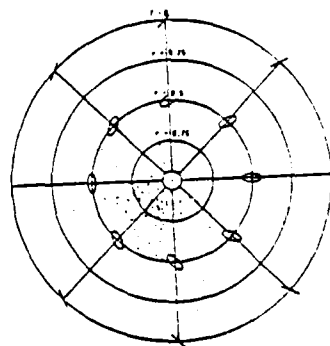


FIGURE 1.19: OPTIMAL POLARIZATIONS
REPRESENTED ON THE POLARIZATION
CHART FOR RAIN TRANSMITTING RHCP

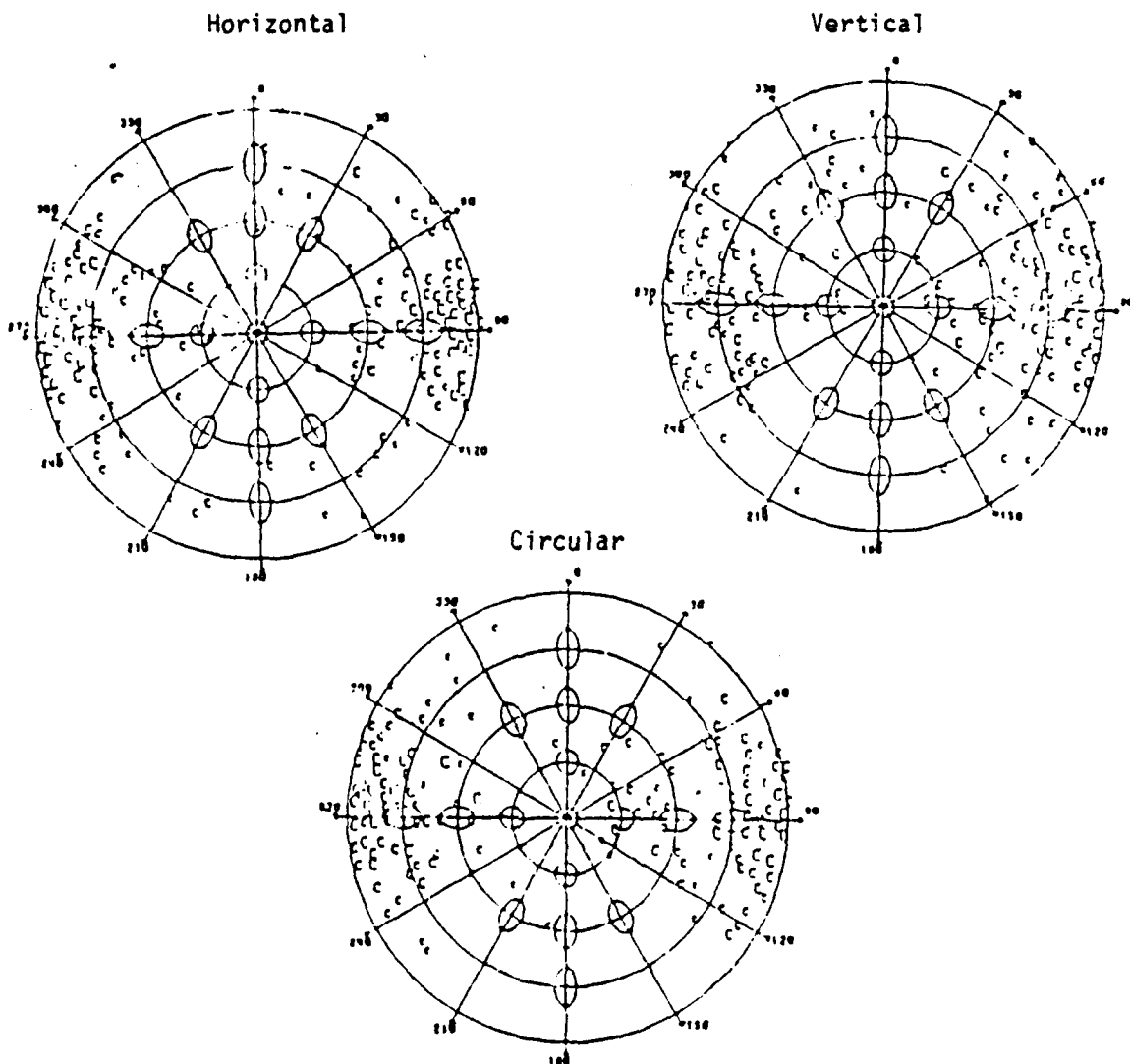


FIGURE 1.18 RECEIVED WAVE POLARIZATIONS USING
A RANDOM DIPOLE SCATTERING MODEL
WITH THE OPTIMAL POLARIZATIONS RE-
PRESENTED ON THE POLARIZATION CHART

In Figure 1.18, plots of the optimal polarizations are given for rain. These plots for rain on the polarization chart were obtained from Poelman (1983) of the SHAPE-TC. The prescribed clustering distribution is again evident and the statistics of this distribution will be given in the next section.

1.10.13 Mean and Spread of the Optimal Polarizations for Completely Polarized Signals

For dual-polarization radars that can switch between orthogonal polarizations for each transmitted pulse below the decorrelation time, the particles within the radar volume were assumed to be stationary; thus, optimal polarizations could be obtained as in the completely polarized case.

Recalling that the scattering matrix transformed to the optimal polarization was given by:

$$[S'] = \begin{bmatrix} S'_{11} & S'_{12} \\ S'_{12} & S'_{22} \end{bmatrix}$$

or

$$[S'] = S'_{12} \begin{bmatrix} \eta'_{11} & 1 \\ 1 & \eta'_{22} \end{bmatrix}$$

$$\text{where } \eta'_{11} = \frac{S'_{11}}{S'_{12}} \text{ and } \eta'_{22} = \frac{S'_{22}}{S'_{12}}.$$

When optimal polarizations are calculated as in Section 1.10.8, a distribution of co-pol nulls will then result from fluctuations due to the motion of the target.

The mean optimal polarization can be given as:

$$\bar{\alpha}_1 = \frac{-\eta'_{11}}{2} \quad (1.10.54)$$

when polarization 1 is being transmitted,
and

$$\bar{\alpha}_2 = \frac{-\eta'_{22}}{2} \quad (1.10.55)$$

when polarization 2 is being transmitted.

In Section 1.10.2, it was shown that S'_{11} , S'_{12} and S'_{22} were assumed Gaussian and uncorrelated. Thus, η'_{11} is also Gaussian.

Now, from equations (1.10.42) and (1.10.54), it can be seen for polarization 1 being transmitted the mean of the square of EDR becomes:

$$\langle |\eta'_{11}|^2 \rangle = \frac{\langle |S'_{11}|^2 \rangle}{\langle |S'_{12}|^2 \rangle} = \frac{J'_{11 \min}}{J'_{22 \max}} = \frac{\det[J']}{(\text{Tr}[J'])^2} \quad (1.10.56)$$

Since $\langle |\eta'_{11}|^2 \rangle$ is assumed to be a zero-mean Rayleigh distribution (i.e., $\eta'_{11} = 0$), $\langle |\eta'_{11}|^2 \rangle$ becomes the mean square deviation, and the root mean square deviation (spread) of the co-pols distributed on the Poincaré Sphere is given by:

$$\sigma_{cp} = \frac{\det[J']}{2(\text{Tr}[J'])^2} = \sqrt{\frac{1 - P^2}{2}} \quad (1.10.57)$$

The spread has general validity because all optimal polarizations represented on the Poincaré Sphere are unique. It should be noted that the spread can be shown to be identical for the transmission of polarization 2 and can be shown to be compatible with the mean and spread developed for the partially polarized case (Nespor 1983).

1.10.14 Summary

The equivalency of the two formulations for partially polarized waves were presented. The co and cross-polarization null concept was then introduced and is looked at from a statistical point of view for both completely and partially polarized waves. The optimal polarizations is then formed in terms of the relevant measurables from circular dual polarization radars. Then expressions for the mean and the spread of the co-polarizations plotted on the polarization chart were presented but no attempt was made to discuss the applicability of these statistics, although applications to radar meteorology do exist [9].

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1.11 APPLICATION III: OPTIMIZATION OF USEFUL TARGET-VECTOR SIGNAL vs. CLUTTER AND NOISE

Previous attempts at developing radar detection, discrimination, clutter suppression, classification, imaging, and identification algorithms for m-to-mm-wave radar applications have been somewhat overly hasty and very heuristic, based mainly on standard single-channel (scalar) statistical detection/estimation/modulation theory. These simplistic scalar approaches can no longer be applied in the polarimetric vector case of m-to-mm wave seeker radar applications, which is not only a considerably more difficult problem, but of a different nature all together. We are no longer dealing with a single channel (scalar) noise problem, but in addition to the inherent systems noise polarimetric multi-channel (5 independent channels for monostatic reciprocal cases, whereas 7 independent channels for the general monostatic non-reciprocal and/or bistatic asymmetrical case), target/clutter signatures must be superimposed. With increasing frequency, clutter possesses very strong polarization-dependence in the m-to-mm wave spectral region, particularly for those wavelength domains within which the scale-length of heterogeneous clutter cell meteorites become of the order of the operating wavelengths. For example, propagation through a heterogeneous scattering/absorbing medium, densely-packed clutter-meteorites (such as hydrometeorological disturbances) dust, smog, etc. a polarimetric radiative transfer approach (Pomraning 1973; Ishimaru 1978) is required, and simplified projection tomographic down/cross-range target imaging methods no longer apply as is shown in Yang and Boerner (1982). As was clearly demonstrated in studies by Kennaugh (1949-1954), Huynen (1982), Mieras et al (1982), Graf (1981-1983), Root (1981), etc. there exists a significant number of types of major air-to-surface clutter, chaff, industrial construction clutter, dummy targets, that have radar signatures RCS similar to that of the desired targets. Therefore, a new, wide open, multifaceted approach must be taken as was deliberated in great detail in the next section of this paper, during the summary on Vannicola's approach (1981).

In the following, only brief summaries of and mainly references to the underlying theories, of basic assumptions, and of measurement approaches are made, as details of these have been reported by the authors within other papers contained within the Proceedings of the Second Workshop on Polarimetric Technology (May 1983).

1.11.1 Basic Polarimetric Theory

In this section we will use the notation, formulation, and sign conventions developed in our reports produced within the Electromagnetic Imaging Division, Communications Laboratory, Electrical Engineering & Computer science Department, University of Illinois at Chicago, as summarized in the published Proceedings of the Second Workshop on Polarimetric Technology (May 1983: Huynen, Davidovitz & Boerner), and the M.Sc. thesis of Chan (1981).

In the following, we will make use of the scattering matrices $[S]$, $[P]$, and $[M]$, $[J]$, and optimization procedures will be applied upon the resulting received power expressions.

1.11.2 Basic Assumptions on Radar Measurables

We will refer to Beker and Boerner (1983), in which most of the applicable methods of recovering the complete radar scattering matrix from pure and/or mixed polarization base, amplitude-only, amplitude-plus-relative-phase mea-

surements are derived in detail. In the following, it is assumed that complete scattering matrix information can be obtained.

In increasing order of complexity we will, in the following, first deal with the idealized coherent cases for which the [S] and [P] matrices apply; and then for the partially coherent cases in which the [M] and [J] matrices must be used.

No use will be made here of polarimetric down/cross range profiling and/or polarimetric relative target-clutter and/or intra-target doppler signatures; i.e., for the initiation of this complex subject matter a simplified monochromatic-polarization matrix-only optimization procedure for clutter suppression will be introduced.

1.11.3 Basic Polarization Vector Signal Processing

Following Van Trees (1968), Vannicola (1981) provided a very useful starting point from which to proceed; not only for hypothesis testing, clutter statistical model development, but also for demonstrating how multi-channel polarimetric co-variance testing may be approached. Because Vannicola's paper is so excellent, we need not recapitulate basic theories here, but we refer to his research initiating treatise.

In the following, we will make use of the three specific hypotheses:

H_0 : only target [S] present

H_1 : only clutter [C] and noise [N] present

H_2 : target, clutter and noise present

and we will optimize the following radar contrast functions:

$$w_1 = \frac{H_0}{H_2}; \quad w_2 = \frac{H_0}{H_1}$$

where H_0 , H_1 , H_2 represent the respective powers received at the receive antenna ports.

1.11.4 Basic Polarimetric Radar Pattern Recognition Algorithm Development

Although we ought to consider polarimetric radar recognition schemes also in this section, we refer here to the very recent textbook by Fu (1974) and the extensive Nav-Sea Report by Manson (1983). Therefore, no further details are presented here.

1.11.5 Development of Optimal Clutter Suppression Techniques

From Kennaugh's optimal polarization null theory, it is known that maximum total power will be backscattered if a single stationary radar target is illuminated with a transmitting antenna polarization being the maximum polarization h_m according to Kennaugh (1949-1954; 1952) and Huynen (1970 and 1982), i.e., one of the cross-polarization nulls of the scattering matrix of that target at a particular aspect angle for a given radar frequency.

In case we have two targets to be differentiated and only one transmitting antenna available with variable polarization capability, let one of the tar-

gets be undesirable clutter. The problem here is to find an optimum polarization of the transmitting antenna such that when both targets are illuminated with this sought-for optimum polarization, the total backscattered power ratio between the desired target and the clutter will be maximized (Chan, 1981). First we will assume that both targets are independent, i.e., the presence of one target does not influence the scattering characteristics of the other and vice versa. We note that, in general, there will be partial cooperative target clutter interaction which yet may not be as disastrous as one might assume at first a glance.

There exist several different approaches which will be summarized in the following sub-sections starting with the simplest model and advancing to the most advanced analyzed up to the present.

1.11.5.1 Kennaugh's Maximization of Target-Clutter Contrast of Receiving Polarization: The Radiometric Case.

In the following, a short but rather important most recent contribution of E.M. Kennaugh is first presented. It is assumed that the transmit polarization either is of arbitrarily constant elliptic polarization state, whereas the receive antenna polarization states can be varied so as to maximize the contrast between two partially polarized waves. This problem should be of immediate interest to radiometric or radioastronomic applications, where the transmit polarization is external to the system and only the receiving antenna polarization can be optimized. We reproduce the paper here as it was forwarded to us (Most likely one of/or the last contributions of E.M. Kennaugh to the research discipline he created; Radar Polarimetry).

December 10, 1982

E.M. Kennaugh

MAXIMIZATION OF TARGET CONTRAST BY CHOICE OF RECEIVING POLARIZATION

Ionnadis and Hammers have considered the optimum choice of monostatic transmitting and receiving polarizations to maximize the average contrast between two time-varying targets. The time-variant targets are described by their individual Stokes matrices (A) and (B). Optimum polarizations (in 4-vector notation) \underline{M} and \underline{Y} are found such that the radar contrast of target A over target B is maximized.

$$\frac{\underline{X(A)Y}}{\underline{X(B)Y}} = \frac{\underline{Y(A)X}}{\underline{Y(B)X}} = \text{maximum}$$

We wish to consider a simpler, but important case in which only the receiving polarization is varied so as to maximize the contrast between two partially polarized incident waves. Such a situation might arise in radio astronomy, or in a bistatic radar environment where only the receiving antenna polarization can be optimized, transmitter polarization being fixed, and it is desired to obtain maximum contrast between two different target classes.

Mathematically, we are given two 4-vectors \underline{A} and \underline{B} representing the polarization states of two incident waves:

$$\underline{A} = \begin{bmatrix} I_1 \\ M_1 \\ C_1 \\ S_1 \end{bmatrix} ; \quad \underline{B} = \begin{bmatrix} I_2 \\ M_2 \\ C_2 \\ S_2 \end{bmatrix}$$

where $I^2 > M^2 + C^2 + S^2$ (equality holding for completely polarized waves only), and receiver polarization \underline{X} is to be found such that

$$\underline{X} = \begin{bmatrix} 1 \\ x \\ y \\ z \end{bmatrix}, \quad x^2 + y^2 + z^2 = 1, \text{ and}$$

the contrast of \underline{A} over \underline{B} is maximized:

$$\frac{\underline{A} \cdot \underline{X}}{\underline{B} \cdot \underline{X}} = W, \text{ a maximum.}$$

The solution may be found by decomposing \underline{B} into the sum of a scalar multiple of \underline{A} , plus a coherently polarized wave \underline{C} ,

$$\underline{B} = \lambda \underline{A} + \underline{C}, \quad \lambda > 0.$$

Then,

$$\frac{\underline{A} \cdot \underline{X}}{\underline{B} \cdot \underline{X}} = W = \frac{\underline{A} \cdot \underline{X}}{\lambda \underline{A} \cdot \underline{X} + \underline{C} \cdot \underline{X}}$$

and since the inner products and λ are all non-negative, the maximum value of the ratio W is achieved when $\underline{C} \cdot \underline{X} = 0$. The maximum value of W is $1/\lambda$, where if several values of λ are possible, the minimum is chosen.

Defining

$$\overline{AB} = I_1 I_2 - M_1 M_2 - C_1 C_2 - S_1 S_2, > 0$$

$$b = I_2^2 - M_2^2 - C_2^2 - S_2^2, > 0$$

$$a = I_1^2 - M_1^2 - C_1^2 - S_1^2, > 0$$

the maximum contrast W is given by

$$W = \frac{\overline{AB}}{b} + \left(\frac{\overline{AB}}{b} \right)^2 - \frac{a}{b}$$

and the value of λ by $\lambda = 1/W$. Knowing λ , the value of \underline{C} can easily be determined, and the vector \underline{X} by $\underline{C} \cdot \underline{X} = 0$.

Examples:

$$\underline{A} = \begin{bmatrix} 4 \\ 3 \\ 2 \\ 1 \end{bmatrix} \quad \underline{B} = \begin{bmatrix} 3 \\ 2 \\ 0 \\ 2 \end{bmatrix} \quad \begin{array}{l} \overline{AB} = 4 \\ b = 1 \\ a = 2 \end{array}$$

$$\underline{B} = \lambda \underline{A} + \underline{C}$$

$$W = 4 + \sqrt{14} = 7.7417$$

$$\lambda = .129171$$

$$\underline{C} = \begin{bmatrix} 2.48331 \\ 1.612478 \\ -.258342 \\ 1.870829 \end{bmatrix} \begin{bmatrix} 1 \\ -.64933 \\ .10403 \\ -.74336 \end{bmatrix}, \text{ optimum polarization}$$

We note that it may be useful to further expand on this specific "degenerate" target/clutter optimization problem by assessing a fixed incident polarization state/basis to be given, with receive polarization states being made adaptive in which case the mixed polarization base measurements methods outlined in Beker and Boerner (1983) should be used.

1.11.5.2 Kozlov's [S]-Matrix Optimizatoin Approach: Kozlov (1969)

(a) [S] Matrix Approach: Kozlov (1979) introduced a method of finding the optimum polarization which involves transformation of the radar scattering matrices $[S_T]$ and $[S_C]$ of the target and clutter to a preferred polarization base. The solution expressed in terms of the eigenvalues (x-pol nulls) and minimal polarizations (co-pol nulls), as well as the geometric angle between the two sets of eigenvectors all being plotted on the Poincare sphere. We note, this model assumed two coherent targets with coherent target interaction which does not satisfy the realistic case of target vs. clutter interaction encountered in radar practice.

1.11.5.3 Chan's Optimization of the Extended Graves Power Matrices $[P_H], [P_V]$:

Chan (1981) used a simplified method of optimizing the merit factor

$$q = \frac{(\underline{h}^t)^T [P] \underline{h}^t}{(\underline{h}^t)^T [G] \underline{h}^t}, \quad [P] = [P_H] + [P_V] \\ [G] = [G_H] + [G_V]$$

where $[P]$ and $[G]$ denote the power matrices for target and clutter, respectively. From this analysis, Chan was able to show that the normalized optimum transmitting antenna polarization can be related to clutter co-pol null and that of optimum receive antenna to target cross-pol null, and vice versa. Substantial additional studies are required for the interpretation of these interesting results. We note that a coherent description for both target and clutter is underlying this approach, and thus it is not applicable to the realistic case encountered in radar practice.

It is also shown in Chan (1981) that for the case of identical transmit/receive antenna systems, the optimum polarization for either case (a) or (b) results in the choice of the co-pol nulls (one for receive, the

transmit, or vice versa) of the clutter scattering matrix which was the conclusion arrived at earlier by Kennaugh (1949-1952) using a different optimization method.

1.11.5.4 Optimization of the Mueller Matrices for the Coherent Target and Clutter Case

The same principle applies when the target and clutter are expressed in the Mueller matrix domain. The Mueller matrix of "coherent clutter" can first be converted to a scattering matrix with relative phase (Boerner et al, 1981), upon which its co-pol nulls can be calculated. Again, when either of the clutter co-pol nulls is used as antenna polarization, the power returned from the clutter is minimum and the return from the target can be maximized. The question arises, however, how one is to recover the averaged mean polarization states and its variances as is discussed in Sections 1.11.5.5 and 1.11.5.6.

1.11.5.5 Ioannidis and Hammer's $\langle [M] \rangle$ Matrix Target vs. Clutter Optimization Approach (Ioannidis and Hammers 1979)

However, if the average Mueller matrices $\langle [M] \rangle$ for either or both of the distributed target and clutter are to be used, the above relations and derivations are not valid. Ioannidis and Hammers provided a first approach to the problem by using a Lagrangian multiplier method to develop an algorithm to find the optimum transmitting and receiving antenna polarization combination for target discrimination in the presence of background clutter. Both the target and clutter are represented by their average Mueller matrix; however, no evaluation in terms of the optimal target/clutter polarization nulls are possible because Huynen's N-target (target plus noise) decomposition theorem was not integrated into the method.

1.11.5.6 Application of Huynen's Decomposition Theorem to the Ioannidis-Hammers Method

The clutter model is given by matrix $[D]$; the target by matrix $[A]$. Huynen has given the decompositions of both $[D]$ and $[A]$ in terms of "single average target" plus N-target residue.



As expected, the dipole cloud is in the average a sphere-type target plus target noise (see orientation-independent targets in Huynen 1982: Revisitation).

The single average target obeys the rules for single objects: $[Q_M] = 0$ and the basic trace-rule. The residue N-target satisfies:

$$B_0^N > 0, \text{ and } B_0^{N2} > B^{N2} + E^{N2} + F^{N2}, \text{ as required.}$$

Example of Target Decompositions

$$[D] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & .5 & 0 & 0 \\ 0 & 0 & .5 & 0 \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} + \frac{1}{2} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

dipole cloud
[D]
= flat plate
[M_{AVE}]
+

+

Residue: [N_D]

Example used in G.A. Ioannidis and D.E. Hammers' paper:

$$\begin{aligned}
 [A] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & .63 & .22 & .43 \\ 0 & .22 & .37 & -.75 \\ 0 & .43 & -.75 & 0 \end{bmatrix} &= \begin{bmatrix} .874 & 0 & 0 & 0 \\ 0 & .689 & .323 & .43 \\ 0 & .323 & .311 & -.75 \\ 0 & .43 & -.75 & -.126 \end{bmatrix} + \begin{bmatrix} .126 & 0 & 0 & 0 \\ 0 & -.059 & -.103 & 0 \\ 0 & -.103 & .059 & 0 \\ 0 & 0 & 0 & .126 \end{bmatrix} \\
 \text{averaged target} & \qquad \qquad \text{single average target} & \qquad \qquad \text{residue N-target} \\
 [A] & \qquad \qquad \qquad [M_{AVE}] & \qquad \qquad [N_T]
 \end{aligned}$$

Condition for single object: Let $s = Mg = s_0^2 - s_1^2 - s_2^2 - s_3^2 = 0$

$$\begin{aligned}
 \text{scattered return} & \qquad \qquad [R] = \begin{bmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{bmatrix} \\
 \text{or } R \cdot s = 0 \text{ gives: } & \text{MRMs} \cdot s = 0
 \end{aligned}$$

Let $MRM = Q$. Then for all terms in Q except the term proportional to R in Q , we have:

$$Q_R = 0$$

1.11.5.7 Basic Recommendations for Further Analyses on Clutter Decomposition Problems

Although a considerable amount of detailed studies exist, by no means has a unique solution to the problem been found. Therefore, it is recommended here that with a thorough study of the three recent pertinent Russian books (Kanareykhin et al, 1966; 1968 and Bogorodsky et al, 1978) and other Russian publications, the initiating studies by Kennaugh, Kozlov, Ioannidis and Hammers, Chan, Zhivotovskiy, Huynen et al be extended, treating the optimization procedures for specific polarization transceiver antenna composition for the coherent, and in particular, the partially coherent cases.

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CHAPTER II

II. ASSESSMENT OF CURRENT STATE OF THE ART, RECOMMENDATIONS, FUTURE
TRENDS AND BENEFITS

Synopsis

Whereas, in Chapter I we provided an overview of the integral disciplines of high resolution radar polarimetry spelling out our contributions and presenting major references, in Chapter II we will assess the current state-of-the-art in high resolution radar polarimetry, provide suggestions for program restructuring of the National Polarimetric Radar Research effort, we will identify unresolved problems, fields and disciplines, and we will assess the benefits, relevance and timeliness of stepping up support for the important newly evolving technology.

- II.1 Assessment of the Current State of Theory, Metrology, N-Dim Vector Signal Processing, N-Dim Image/Pattern Recognition, and Polarimetric Hardware Design.
- II.2 Fields of Application.
- II.3 Restructuring and Reorientation of the National Polarimetric Radar Research Effort.
- II.4 Identification of Specific Unresolved Problems, Underdeveloped Fields and Disciplines.
- II.5 Relevance, Timeliness and Benefits of Increasing Support for High Resolution Polarimetric Radar Technology.

II.1 ASSESSMENT OF THE CURRENT STATE OF THEORY, METROLOGY, N-DIM SIGNAL PROCESSING, N-DIM IMAGE/PATTERN RECOGNITION, POLARIMETRIC RADAR HARDWARE DESIGN

II.1.0 Introduction

We at the Electromagnetic Imaging Division (EMID), Communications Laboratory (CL), Department of Electrical Engineering & Computer Science (EECS), University of Illinois at Chicago (UIC) (see Description of Facilities in Chapter VI) have put together one of the strongest research forces on advanced radar polarimetry that can possibly be collected at an academic research institution. Next to having such pioneers in radar polarimetry as the late E.M. Kennaugh, J.R. Huynen and A.J. Poelman, being full adjoint members of our laboratory, we are collaborating very closely with renown experts as, for example, G.A. Deschamps, Y.T. Lo, C.L. Bennett, R.M. Barnes, R. Larson, A.K. Fung, S. Weisbord, A.L. Hansen, T. Sarkar, M. Thiel, K. Umashankar, A. Taflove, A.J. Blanchard, S. Theis, we are enjoying the expert support from such governmental researchers as, L.W. Root, V.C. Vannicola, D. Taurony, D.R. Wehner, D. Reade, D. Kerr, M. Skolnik, F. Nathanson, O. Kessler, D. Trizna, J. Gobien, G. Morse, R.A. Ross, K. Steinbach, G. Winkler, and R. Dinger; and our research team has been selected to provide consulting services in advanced radar polarimetry for major national radar design/development and manufacturing companies including, for example, Raytheon, Bendix, Martin-Marietta, General Dynamics, Honeywell, Bell Aerospace Textronix, Ford Aerospace, Motorola, Systems Planning Corporation, and Boeing Aerospace Corporation just to mention a few. Given this basis, it is one of our prime objectives to verify the theory of radar polarimetry and to isolate still unresolved questions pertaining to its most successful application in tactical and surveillance radar technology. Based on literature surveys carried out within our laboratory, we will here summarize important accomplishments and identify those problems which still need to be resolved.

Although our research contract efforts are based solely on unclassified background material that is available in the open literature. We, based upon our integrated knowledge, gathered since the very infant beginnings of radar polarimetry, are confident that we will be able to provide expert advice to the National Radar Research Funding Organizations in assessing the current state-of-the-art by transposing the mathematical concepts of analytical continuation to a human mind capable of common-sense analytical reasoning.

II.1.1 Assessment of Theoretical Basics of Broadband Radar Polarimetry

The foundations of the underlying theory in radar polarimetry were undoubtedly and almost completely worked out by the late Dr. Edward M. Kennaugh, Professor Emeritus, OSU, in his 24 reports of 1949-1954 (Antenna Laboratory, OSU, Rept. Nos. 389-1-389-24 and subsequent Report Nos. 612-1 to 612-16). About 90% (ninety percent) or more of the material presented in the really outstanding dissertation on Radar Target Phenomenology by J. Richard Huynen (1970) is contained in various original "counterpoint" transformations within the above mentioned pensive reports. Rept. No. 389-12 (March 1, 1952) presents the M.Sc. Thesis of E.M. Kennaugh for which reason we have dedicated this report in his name. Notwithstanding the enormous basic efforts of Dr. Kennaugh, and then the intelligibly fine-tuned interpretation of Dr. Huynen, who introduced the important N-target decomposition theory for distributed statistical radar targets described by a time-averaged Stokes reflection or Mueller matrix, there still exist various unresolved problems

which need to be addressed to make the theory of radar polarimetry complete:

- a) Monostatic, Coherent, Reciprocal Radar Scattering Case:
More or less, the theory is complete, including the transformations from [S] to [M] to [P] and/or [J] matrix representations and vice versa; Kennaugh's optimal polarization null theory; Huynen's N-target [M] matrix decomposition theory (still not complete); Poelman's dynamic polarization fork motion (still incomplete); Mieras' vector scattering center interactive clutter interpretation (not complete); Kennaugh's maximum target vs. clutter contrast function (not complete). The monostatic non-reciprocal case still must be solved.
- b) Bistatic, Coherent, Non-reciprocal Radar Scattering Case:
Research on this problem was initiated only recently in our laboratory as is documented in the work of Mr. Marat Davidovitz (1983). Only the coherent case was treated and more research needs to be accomplished relating to proper interpretation of the results. This bistatic polarimetric theory also applies to the monostatic asymmetric case which is of great importance to the problem of detecting radar targets in anisotropical heterogeneous clutter environments.
- c) Time-domain Representation of Wave/Target Polarization State Interaction:
Legitimately, the scattering matrix concept applies to the frequency domain, i.e. polarization presentation on the polarization sphere is a frequency-domain "IMPEDANCE" concept and thus, if generalized into the time-domain will cause the failure of [S] matrix representations for poly/panchromatic cases. Therefore, a coherence matrix approach is required as is being analyzed in the M.Sc. Thesis of Mr. Jerald D. Nespor (June, 1983), so that the mean optimal polarization nulls and their variance or spread can be determined. There still exist many open theoretical problems which require an immediate solution so that the dynamic problem of polarimetric radar target detection in a statistically varying random clutter environment can be solved. Because of the urgency of having such a complete polarimetric clutter handling theory available, all efforts will be made in advancing the quasi-coherent optimal polarization null statistical averaging methods.
- d) Polarimetric Maximum Contrast Operator:
For the monostatic coherent case, Kennaugh, Kozlov, and later, Ioannidis and Hammers developed concepts of defining maximum contrast merit factors, and Poelman extended this method further to develop a maximum contrast operator theory which is applicable also in the statistical random clutter case. Currently, we are carrying out collaborative studies with E.M. Kennaugh (before his untimely departure), along with J.R. Huynen, A.J. Poelman and V.C. Vannicola in advancing their maximum contrast operator vector signal processing theory so that it can be applied in practice utilizing advanced methods of decision and estimation theory (Van Trees, Vols. 1-3): See "Proceedings of NATO-ARW-IMEI-1983".

e) Polarimetric Target Shape Down-Range Imaging:

We at EMID-CL-UIC have contributed profoundly to radar target shape imaging by extending existing scalar wave Physical Optics approximate Inverse Scattering techniques to the polarimetric vector case, as is being explained in great detail in M.Sc. Thesis by B-Y. Foo (1983) and the forthcoming dissertations of Mr. Foo/C-M. Ho (1980)/C-W. Yang (January, 1984)/S. Saatchi (1983). Although substantial advances have been made, it must be emphasized that there does not exist, at the present time, a suitable mathematical approach to handle the creeping wave umbra/penumbra distortion towards complete polarimetric down-range shape reconstruction.

This problem of polarimetric down-range shape reconstruction is also related closely to the question of the polarimetric dependence of the residues associated with the target natural eigen-resonances as is being treated in Section I.5 by Mr. Vithal K.S. Mirmira (198), in which deep insight into this problem is displayed.

f) Polarimetric Target Cross-Range Imaging:

One of the most fascinating properties of the scattering matrix transformation invariances

$$\text{span}([S(A,B)]) = |S_{AA}|^2 + |S_{AB}|^2 + |S_{BA}|^2 + |S_{BB}|^2 = \text{invariant}$$

and

$$\det([S]) = |S_{AA}S_{BB} - S_{AB}S_{BA}| = \text{invariant}$$

come to light on electromagnetic cross-range image formation, as for example, in synthetic aperture radar and its related techniques of RAR, SLAR and ISAR. To obtain higher resolution cross-range maps, we do require, pixel by pixel, complete relative phase scattering matrix measurement information, as is considered in Section I.2 (W-M. Boerner, May 1983).

To fully exploit this interesting concept of target vs. noise polarimetric pattern recognition method, still a great deal of two-dimensional optimal polarization null filtering is required.

g) Polarimetric Vector Diffraction Imaging Through Inhomogeneous/-Heterogeneous Media:

One of the most difficult problems facing us in any kind of seeker robotic target detection mode is the fact that the target sits deep in heterogeneous clutter, i.e., the interrogating wave will suffer severe ray-path bending and diffractive deterioration before it returns to the receiver. In turn, substantial corrections to wavefront deformation must be made, and for an electromagnetic wave the problem becomes vector in nature, i.e., we are dealing with a polarimetric vector diffraction tomographic imaging problem.

h) Conclusions:

It was shown that the basic polarimetric radar theory is relatively well developed, but a long shot away from being perfected and completed. Yet, there does exist a broad, thorough and deep wealth of knowledge which is based on exact, unique electromagnetic theory, and it can not be blatantly ignored as was the case in various national polarimetric radar seeker research/development/-manufacture efforts.

Every possible effort, as costly as it may be, needs to be made by the national radar R/D/M corporations and governmental research institutes to be involved in the rapid development of such a very demanding, complex and sophisticated (math/phys/eng/env/tech/-manu/appl) field as broadband high-resolution polarimetric radar robotics proves to be. The national radar research efforts must develop a very strong basic research effort and, at the same time, integrate academic research institutions into its endeavors. We at EMID-CL-EECS-UIC, Chicago are prepared to contribute a major research effort in this rapidly advancing novel field of polarimetric radar target handling.

II.1.2 Assessment of Polarimetric Radar (Antenna) Metrology

The task of designing a high-resolution polarimetric measurement system that encompasses widely varying capabilities in the m-to-mm-wavelength region is one in which a trade-off may have to be made in terms of performance, quality and cost restraints. Unfortunately, the latter has, in the past, outdone, by a long shot, the former without exception due to the extremely poor comprehension of the enormous capabilities of polarimetric radar measurement theory and technique in advancing radar target detection in the most severe clutter conditions. An advanced modern polarimetric RCS matrix measurement system must accurately control amplitude to within less than 1dB and relative phase to within less than 5° error margins of a wide-band transceiver system which has the capability of being agile in frequency, phase, time, amplitude, polarization as required by the highly demanding high-resolution polarimetric radar imaging robotic target classification/imaging/identification modes of radar operation.

It is evident from this long list of required polarimetric radar antenna measurement performance items that there exist a great many unresolved problems which will require thorough polarimetric research efforts over, at least, the next ten (10) years or more. The sad part of the story is that in the past, many excellent research contracts in the field of polarimetric antenna design were clearly denied because of the following inexcusable reasons, here quoted from Contract Reviews:

"... Who really needs more than 25dB isolation of co/co and cross/co channels in polarization ...

... Why would one need more than 18dB suppression in sidelobes for polarimetric reasons ...

... Why deal with high polarization purity at all when one does not need it in an incoherent system, ... etc."

It is deplorable to be made aware of the short-sightedness that may have prevailed within many of the "National Research Supporting Agencies". If, and only if the advanced polarimetric radar manufacturing corporations are made aware of the dismal state-of-funding in advanced polarimetric antenna design, voice their opinions, and are willing to force a major change in governmental funding efforts, will we see a change of this poor performance state of affairs within the USA (which usually means all of NATO/West).

In summary, Polarimetric Radar Metrology requires a BIG SHOT in the arm, and then we should be witnessing a decisive change.

a) Antenna Polarization and Scattering Matrix Metrology:

Although there exist some well done treatise on antenna polarization and scattering matrix measurement principles as has been clearly summarized in Benjamin Beker & W-M. Boerner (1983), W-M. Boerner, et al (1981), J.R. Huynen (1982) and E.M. Kennaugh (1982), there still seems to exist some misunderstanding about how complete polarimetric scattering matrix information is to be recovered from measurements.

We are now convinced that our thorough research, the prime objective of the unified UIC consulting research effort, should remove any further questions; in particular, with respect to the ill-conceived linear polarization sweeping techniques and other polarimetrically incomplete target detection schemes that have been considered recently.

b) Antenna Polarization Purity:

The question of polarization purity in the measurement of antenna polarization and scattering matrix elements still represents a wide open problem, and we refer to the outstanding work of Blanchard and Jean of the Texas A&M, Remote Sensing Laboratory, which is one of the best of its kind available. The electromagnetic antenna reciprocity theorem provides the foundation for describing the interaction between the measurement probe and its environment, and only if high co/co and co/cross channel isolation, as well as extreme sidelobe suppression is attained, will we obtain reliable measurements with the required polarization purity.

Although considerable advances have been made regarding polarization antenna design, we still have a long way to go. Specifically, extensive research funding resources are required for the design of polarization state adaptive antennas with at least 40dB isolation for co/co cross/co channels and 32dB sidelobe suppression for any polarization vector state covering the total polarization sphere.

c) Antenna Polarization State Switching:

One urgent requirement in Advanced Polarimetric Radar Robotics design is the availability of broadband transceiver systems with extremely fast polarization state switching capabilities. The complete relative phase scattering matrix needs to be measured within time frames lying well below the reshuffling time of clutter scattering centers or of the scatterer decorrelation time and with the best available polarization purity. For example, if the

scattering center reshuffling time constant is of the order of 10 to 15 milliseconds, it is desirable to perform one complete scattering matrix measurement within 50 μ sec. and certainly not more than 100 μ sec. in order to average out the propagation path scintillations by changing transmit polarization states. Therefore, antennas with mechanical switches must be considered outmoded and we require fast electronic switching (pindiodes, etc.) of transmit/receive antenna polarization states (we note that transmit/receive antenna polarization states need not be the same; and the measurement set-up may be either mono-static or slightly bistatic).

There now exist several polarization antenna manufacturers (Raytheon, EMS-Inc., EMI, Siemens) who can provide a fast switching polarization transceiver system; however, only over rather limited bandwidths and not over all of the desired frequency regions of the m-to-mm wavelengths.

Considerable R&D funding efforts will have to be made to improve on the current state of this urgently required technology.

II.1.3 Assessment of N-Dim Vector Signal Processing Theory/Technique: Development of Optimal Clutter Suppression Techniques

An assessment of and guidelines are developed on how the polarization vector intensity (Stokes' vector) of the polarimetric broadband pulse-doppler radar target return can be optimized vs. polarimetric clutter return and systems-inherent noise using recent advances in detection, estimation, modulation and optimization theory. It is shown that we are dealing essentially with the mating of vector scattering theory and multi-channel signal processing in advanced radar polarimetry.

Whereas it is certainly essential to obtain a thorough and deep understanding of the underlying coherent and partially coherent basic electromagnetic theory of broadband high resolution radar polarimetry, we must also, at the same time, advance methods of multi-channel polarization vector signal processing with the aim of maximal clutter suppression and high resolution target imaging. In this section we will, therefore, attempt to develop guidelines on how the polarization vector intensity (Stokes' Vector) of the polarimetric broadband pulse-doppler target return can be optimized versus polarimetric clutter return and systems-inherent noise using recent advances in detection, estimation, modulation, and optimization theory, as for example, developed in the 3 volumes of Harry L. Van Trees on this subject matter.

In effect, we are dealing with the coordination and mating of vector scattering theory and multi-channel signal processing in advanced radar polarimetry. This is an exciting new interdisciplinary research field, and, hence, still a great effort needs to be expended before useful self-consistent solutions to the problem of radar target polarimetric vector signal discrimination vs. clutter and noise can be implemented in practice.

Therefore, only a preliminary analysis can be given here upon which we will have to expand and advance rapidly within the forthcoming research granting periods. In the following, first, a succinct literature review on existing

polarimetric radar optimal clutter suppression techniques is given and followed by more detailed outlines on the basic underlying detection/estimation/optimization model theory and on existing methods such as Kennaugh's initial hypothesis being followed by the approach of the Russian polarimetrists such as Varshavchuk and Kobak (1971), Kozlov (1979), Zhivotovskiy, Pavlov, Kanareykin and Bogorodsky (1983-84): the extensions of these approaches by RADC under Ionnidis, Hammers, Rosien, Bell, Fujimota, Nemit and Klein; the clever approach of Chung-Yee Chan; Poelman's introduction of the polarization transceiver antenna control and the dynamic polarization fork indicator console; and last but not least, Vannicola's generalized approach to the problem.

Literature Review: Traditionally, radar systems mainly employed for transceiver antenna polarizations either a circular or linear polarization basis, where horizontal and vertical polarizations were most often used. It was Kennaugh (1949-1954) who first suggested that the ability of the radar to vary antenna polarization, i.e. polarization agility and/or transceiver polarization adaptability, will result in a significant increase in the magnitude of the backscattered power gathered from a target embedded in clutter. These early, well documented claims of Kennaugh (1952), expressed in terms of the optimal polarization null signatures of the 2×2 radar scattering matrix, were further substantiated by Huynen (1970), expanding on Kennaugh's five independent target characteristic angle descriptors and the Mueller matrix notation (1982) for decomposing a distributed radar target, as for example, clutter plus target, into an average single target $[M_T]$ and some target residue $[M_n]$, denoted by Huynen as "target noise".

We should emphasize here that the denotation "target noise" is/could be misleading since the target residue has no relationship with any kind of "noise" and/or "clutter" in the standard textbook definition, and it represents some extra information to which no useful meaning can hitherto be attached except the variance of the location of the optimal polarization nulls about their main location on the polarization sphere (Nespor, Agrawal and Boerner, 1984).

In the coherent case of an isolated single target, Kennaugh's optimal polarization null theory and Huynen's target characteristic angle parameter description applies directly, i.e., using the maximum polarization (cross-pol null) will result in maximum reflected power reception; and conversely, if the antenna polarizations are those of the co-pol nulls of the target scattering matrix, then theoretically no reflected power will be received in the co-polarized channel. However, in the partially coherent case of allocating a stationary or moving target with intra-target motion of scattering centers in random non-stationary clutter, the problem is more complicated and it was Kennaugh (1952) who first introduced a target vs. clutter optimizing contrast merit factor, a concept which was further pursued by Varshavchuk and Kobak (1971), by Kozlov (1969) and many other Russian scientists who introduced a method of finding the optimum polarization which involves transform-

ation of the scattering matrices of the target and the clutter to a preferred polarization basis. The contrast function is expressed in terms of the eigenvalues and the geometric angle between the two sets of eigenvectors of the scattering matrices plotted on the Poincare sphere, i.e. maximizing the separation of target vs. clutter polarizations or, in other words, moving the useful target signal out of the clutter-infested regions of the polarization sphere.

Following the analyses of Varshavchuk and Kobak (1971) and those of Kozlov (1969), Ionnidis and Hammers (1979), in consistency with their approaches, made use of the Lagrangian multiplier method to develop an algorithm to find the optimum transceiver polarization for target discrimination in the presence of background clutter and noise. Both the target and the clutter are represented by their average Mueller matrices without taking recourse to Huynen's N-target decomposition theory (1970,1982). Huynen used their results and most recently provided examples of how his N-target decomposition can be used to obtain further insight into this problem.

A rather systematic approach to the problem of recovering the optimum polarization for target vs. clutter discrimination is presented in Chapter 7 of the M.Sc. thesis by Mr. C-Y. Chan (1981), where first, a method of determining the optimum polarization for maximum total backscattered power ratio between target and clutter, and then, a method for obtaining the optimum polarization polarization for minimum power reception from clutter in target vs. clutter discrimination is discussed using contrast merit functions similar to those first proposed by Kennaugh (1952) and a novel formulation of Graves' power scattering matrix. A rigorous application of this method requires the recovery of the mean co-pol/cross-pol clutter nulls and their spread, which requires the measurement of the coherency matrix, i.e., the Stokes parameters from which the mean optimal polarizations, as well as its variances, can be extracted, as is analyzed in great detail in the M.Sc. Thesis of Nespor (1983).

Undoubtedly the most successful advances in the radar problem of polarization vector signal processing for clutter suppression were made by Poelman (1976-1983) who has built several versions of complete scattering matrix radars utilizing the optimal polarization null properties of target and/or clutter, and developing the Dynamic Polarization Fork Indicator Console and the Polarization Transceiver Control Console as was summarized in detail in Boerner (STAS 1914,1981). Most recently he has introduced the concept of polarization vector translation in radar data postprocessing whereby the received fields are translated on the polarization sphere by means of mathematical vector transformation onto the fixed location composite filter area of a multi-notch logic-product polarization suppression filter. The resulting concept not only promises to be a powerful tool for improving target detection capabilities through the suppression of unwanted signals, but it has now also been demonstrated in real-time implementation (Poelman, 1976-1984).

We note here that various other methods of clutter suppression and target enhancement have been proposed recently by Root (1981), utilizing the concept of even and odd bounce conductive reflectors as explained, for example, by Mathur (1982) and Dunlap (1981) and utilized by Raven (1981), Justus

(1981) and by Mieras, et al (1982). However, as has been clearly demonstrated in the latter report, the even/odd n-bounce conducting reflector concept can be re-expressed rather elegantly in terms of Kennaugh's optimal polarization null concept utilizing Huynen's descriptive target angle parameters (1970, 1981).

In all of the above reviewed methods, use is made only of complete time-averaged scattering matrix monostatic radar returns but doppler down and cross range spread, as well as intra-target scattering center motion were not considered. What, however, is required, is a clutter suppression model for radar scatterers which simultaneously incorporates down/slant range, relative and intra-target doppler and polarization characteristics in a statistical sense. Any scatterer, whether it is being a sought-for target or clutter, can be represented by such a model which was recently introduced in an important study by Vannicola (1981) which deserves our serious attention. The author provides an extension of classical single-channel (scalar) system detection/estimation/optimization theory to the multiple channel (polarization vector) case. It is an initial promoting exposition in which it is assumed that the target environment is a stochastic process consisting of undesired (clutter) scatterers and desired, sought-for (target) properties, each having its own characteristic doppler, range, and polarization properties, but which have not been defined nor analyzed in details required here.

In essence, the following new approach must be taken requiring new methodologies, integrating polarimetric broadband high-resolution down-/cross-range imaging, relative and intra-scatterer doppler and time correlation techniques over, most likely, many windows of the electromagnetic spectrum from about 600MHz to a few THz. The generalized target separation/clutter suppression attack of this advanced polarimetric seeker radar problem encompasses the following elements:

- increase the dimensionality of the radar signal through use of techniques like complete scattering matrix polarization recovery, frequency hopping over many windows, polarimetric cross-/down-range profiling, polarimetric doppler beam sharpening, extended time correction, dynamic polarization fork control, etc.
- utilize the maximum entropy methods currently being developed by Poelman utilizing his multi-notch-polarization-vector transformation filter approach for optimizing the separation of useful target signal from clutter-infested domains on the polarization sphere; further extend this method to include doppler signatures of relative target vs. clutter, clutter, and also intra-target scattering center motion which all possess very distinct multi-channel polarimetric signatures.
- utilize the recently, rapidly advancing science and technology of vector signal detection/estimation/modulation/optimization/classification processing to derive optimal polarimetric pulse doppler separating algorithms, as, for example, developed in the three volumes of Van Trees (1968).
- use advanced pattern recognition methods, extend those to incorporate either Kennaugh's optimal polarization nulling concept, the span invariance of the scattering matrix in polarimetric cross-range imaging modes, and/or Huynen's target invariant angle description as outlined in detail in the M.Sc. Thesis by A.C. Manson (1984).

- design, develop, and use advanced broadband polarimetric radar systems which can produce the urgently required basic complete scattering matrix input data for model development.
- base all work on actual complete polarimetric data until sufficient, accurate, validated polarimetric vector models can be developed.

Because Vannicola's approach does form the basis of any useful future development and implementation of polarization vector signal processing in a doppler and down-/cross-range extended sense, it will require a serious critical review. We note here that a first attempt of attacking this problem is reported in Poelman (1965-1983), dealing with an adaptive approach to polarization vector signal processing.

Last, but not least, we must reemphasize the rather active research mobility in polarimetric radar research demonstrated by Russian scientists in this field, and we refer particularly to four outstanding books on radar polarimetry and its applications (Kanareykin, Pavlov, Potekhin, 1966; Kanareykin, Potekhin, Shishkin, 1968; Bogorodsky, Kozlov, Tuchkov, 1978, Varganov, Zinov'ev, Kanareykin, 1984), and request that the English version of the third and fourth, most recent treatises be made available not only to governmental research laboratories, but also to university and industrial researchers who have a need for using it (Boerner, series of four invited papers for IEEE/AES Journal, 1984).

II.1.4 Assessment of Polarimetric Radar Pattern Recognition Algorithm Design in N-Dim Polarimetric SAR/RAR/ISAR Image Evaluation

Polarimetric pattern classification is a relatively new field attracting interest from many technical groups in remote sensing. The problem is of utmost importance in providing structural information of a target scatterer when 2-dimensional resolution of the target is difficult if not impossible. In effect, it employs all the information available in the electromagnetic field.

Because of the fact that most practical targets are immersed in clutter, the polarimetric information can provide a means of identifying the target in clutter, as well as providing a means to isolate the clutter so a target can be viewed more easily.

Target clutter demonstrates certain features when its backscatter polarization is represented on a unit Poincaré sphere. This was demonstrated by Steven Weisbrod and Lee A. Morgan when they developed the spherical variance model. In it, they empirically determined that the spherical variance of certain clutter was close to zero when successive measurements were taken. Measurements in the presence of a target, however, showed a larger spherical variance. In lieu of this result, one could use the complete information, i.e., amplitude and polarimetric state at a given frequency to develop the essential feature vectors of the target and clutter. The technique can then be applied at other frequencies for the same target and clutter. The incentive for processing data at multi-frequencies is that the feature vector at different frequencies of the same target will vary. This fact will provide a means for greater discrimination of signals when the feature vectors at a particular frequency are difficult to distinguish.

Since the amplitude and polarimetric information can be represented with the Stokes vectors, this can be used initially as our pattern space. The mean and variance from the mean. Then the covariance matrix can be constructed from then weighted points. Finally, a similarity transformation can be taken of the covariance matrix with the eigenvectors corresponding to characteristic sample variances and the eigenvectors corresponding to measurements. The measurements corresponding to the smallest eigenvalue are the most reliable. If the samples take on an approximately normal distribution, they will fall in a cluster with its center at the mean, and its shape defined by the covariance matrix. The loci of points of constant probability are hyperellipsoids with the principal axes in the directions of the eigenvectors of the covariance matrix and the lengths of these axes determined by the eigenvalues.

The span-invariant plays a very important role in cross-range formation, using data recovered from dual polarization SAR/RAR or, microwave holographic imaging methods. Whereas, in recent partial polarimetric SAR/RAR image evaluation only $|S_{HH}|^2$, $|S_{VV}|^2$ or $|S_{HV}|^2$ had been recorded and rarely superimposed, we must emphasize here that it is essential and absolutely necessary to record total polarimetric information on $[S]$, i.e., amplitude and relative polarimetric phase and to provide incoherently superimposed images for the σ_{HH} , σ_{VV} and $\sigma_{HV} = \sigma_{VH}$ returns according to the span invariant

$$p = \text{span}\{[S(A,B)]\} = |S_{AA}|^2 + |S_{BB}|^2 + 2|S_{AB}|^2$$

which is polarization invariant and contains complete cross-range image information. Recording of either $|S_{AA}|^2$, $|S_{AB}|^2$, and/or $|S_{BB}|^2$ is incomplete and will result in the loss of information.

Experiments carried out in the last few years have demonstrated the relationship between the shape and orientation of a target and the location of its co-pol and cross-pol nulls. It has been observed that different types of clutter such as, for example, that of chaff, vegetation, sea waves, etc., have different clustering of the co-pol and cross-pol nulls about different mean polarization nulls. Thus, a detailed experimental study of the co-pol and cross-pol nulls of different types of targets and clutter and its dynamic polarization fork motion on the polarization sphere as functions of aspect, frequency and time will provide a data base which is vitally needed for exploiting the full potential of radar polarimetry.

Specifically, it can be shown that in case complete amplitude and relative polarization phase information of the scattering matrix for each pixel is available, then the optimal polarization null theory can be applied to "null out" undesirable image features (clutter) and to enhance desirable image features (target) by rotating the respective pixel matrix polarization base vectors into the desirable null polarization vector on the polarization sphere. This procedure can be applied to extended clutter regions, segments, contours and other pertinent image features thus, providing a polarimetric pattern recognition matched filter approach.

In conclusion, it is to be emphasized that in high resolution imaging, the polarimetric properties of image formation in the microwave spectral region cannot be neglected. Therefore, the method described here is capable of utilizing complete polarimetric pulse doppler broadband radar modes of operation incorporating both scatterometric down-range, as well as SAR/RAR/IMAR cross-range image formation.

To be able to classify many patterns, it will be necessary to establish a data-base capable of storing and quickly accessing the pattern data. Access speed is of paramount importance if it is to be used in the field. This will be a function of the length of the data used and the interrelationship of this data. In general, speed increases when data records are small and the interrelationship of the elements is extensive.

One such technique is the formulation of the structural information of a target into a relational syntax. This syntax can then be used by a parser to attempt either a top-down or bottom-up parse of the object. Since all the information necessary to construct the target class is incorporated into the syntax, the syntax can be used to provide heuristic information that could be used in guiding an interactive radar system to making verification measurements.

II.1.5 Assessment of Polarimetric Radar Robotic Simulator Design

A major research effort in implementing polarization characteristics of isolated (and distributed) scatterers in radar and remote sensing is being carried out. Due to the fact that an electromagnetic wave is vector in nature, i.e., the polarization state must be given in addition to amplitude, phase and carrier frequency for its complete description, this additional property needs to be taken into consideration for the complete, unambiguous description of electromagnetic wave interaction with material bodies. This in turn implies that a radar, ladar, lidar target may be considered to be a polarization (matrix) transformer, and that there do exist optimal target polarization properties which prove to be of paramount importance to radar target vs. clutter and/or non-cooperative target acquisition, allocation, discrimination, mapping, imaging, identification and classification. This research makes use of these optimal polarization (scattering matrix) null properties which can be expressed in terms of the target polarization fork. Specifically, it has been shown that for moving targets the dynamic polarization fork properties prove to contribute an indispensable target characteristic operator in advanced radar polarimetry. Theoretical, experimental, technical and computer processing aspects of completely integrating this novel target characteristic operator concept into advanced military/commercial radar, as well as airborne and satellite remote sensing systems are being studied actively.

It is the objective to develop and design a complete automated, self-operating radar target characteristics discriminator based upon the optimal target polarization properties. This research will be dealing with the digital real-time recording, storing, filing and processing of complete relative phase radar scattering matrix measurement data, the automated extraction of the optimal polarization null characteristics and its presentation in terms

of the dynamic polarization fork on the polarization sphere or any equivalent useful joy-stick operated display chart. Computer robotics software is to be developed which will allow optimal target classification and identification in milli-second to micro-second time frames, i.e., we will be developing a fully automated, self-operating Dynamic Polarization Fork Indicator named DPFI. The DPFI in parallel with MTI (Moving Target Indicator) and a Doppler signature indicator will be integrated into one polarimetric radar robot "for automated optimal target classification and identification".

Currently, such a system is being implemented at the NATO, SHAPE Technical Center, The Hague, and under the umbrella of a NATO Senior Scientist IMOR Fellowship, we are collaborating with Dr. A.J. Poelman on these exciting developments.

II.1.6 Assessment of Polarimetric Hardware Design Approaches

During the past two decades, polarimetric hardware design was certainly highly advanced placing, however, too much emphasis on developing the least costly approaches and thus, there still exist many untouched component design problems, such as that of dual polarization antenna systems with high channel isolation and sidelobe suppression, for arbitrary elliptical polarization vector bases, fast polarization state (phase) switches for relatively high output power levels, etc.

For example, let us consider the development of the "INTRAPULSE POLARIZATION AGILE RADAR (IPAR)" in which a pulse is encoded by polarization modulation on a subpulse basis mainly using circular (L,R), or linear (H,V) polarization base state modes for the discrimination between even and odd bounce reflections. This is certainly a useful tool in pre-detecting approximate discrimination modes of separating man-made (even bounce: dihedral, quadrilateral, etc) from more likely, natural (odd bounce: flat plate, trihedral, etc.) scatterers; however, IPAR will not provide a "fool-proof" self-consistent discriminator; and, in addition, complete polarimetric scattering matrix information needs to be recovered for the purpose of utilizing the optimal polarization target null information. To accomplish that goal, one needs to modulate between a uniquely chosen set of polarization state basis vectors for the recovery of [S] and [J] and/or [M] as was described in Beker and Boerner (1983), i.e., the IPAR approach of Bob Appling, Jerry Eaves, Sjoberg, Cohen, et al, EES-GIT needs to be much further advanced, providing the required polarization state purity and modulation PRF.

Another example pertains to the design of an adaptive dual orthogonal polarization antenna system for arbitrary elliptical orthogonal polarization vector bases requiring high co-co/co-cross channel isolation (at least 35dB), and sidelobe suppression (at least 28dB). It is found that for narrowband operation for one particular orthogonal polarization basis vector pair this high demand may be achieved, but still an extensive amount of research is necessary to design antennas providing such isolation/sidelobe suppression over a wide frequency and for adaptive polarization states which cover the entire polarization sphere.

It would be desirable to be given access to proprietary and confidential information for assessing the true state of the art in polarimetric radar hardware design. A specialized workshop on the subject matter similar to the two Missile Command Workshops would be advantageous, but such a workshop must be totally restructured so that the National Polarimetric Radar Industry would become enthusiastic about displaying important, novel innovations without fear of repudiation, i.e., we must turn them loose and force them to learn, absorb and further advance their polarimetric knowledge base.

II.2 FIELDS OF APPLICATION

The proposed research will enable investigations to be carried out which have direct and immediate relevance to a wide variety of fields. These include, but are not limited to:

- basic polarimetric signature studies of specifically selected classes of symmetrical, asymmetrical, reciprocal and anisotropic scatterers, in isolation, homogeneous and mixed heterogeneous distributions for the support of analytical model simulation studies of target and/or clutter;
- defense applications such as generation of a data base for the classification of targets and clutter, improvement of target-in-clutter detection, target imaging and identification;
- defense applications such as the development of robust techniques for target detection and identification;
- applications to meteorology including study of dynamic hydro-meteoric states within the radar cell, classification and identification of dynamic precipitation states such as hail, rain, and snow; cloud microphysics; atmospheric electricity and wind shear detection;
- applications to radio wave propagation through turbulent and random media, such as the earth's atmosphere, directly relevant to communication systems design for earth-to-satellite frequency-reuse-propagation links;
- early, instantaneous detection of the general target vector of motion from instantaneous polarization fork precession (gyroscopic motion of cross-pol nulls) from high resolution polarimetric radar measurement data which can be implemented to increase hit accuracy of fire-control radars;
- air traffic control applications, such as analysis of atmospheric turbulence, high moisture wind shear and electric storm effects on air traffic flow, aircraft take-off and landing operations;
- basic polarimetric pattern analysis of SAR/RAR/ISAR imaging systems;
- applications to remote sensing, such as observation of sea state, signatures of different types of vegetation, etc., surface scatter, etc.
- atmospheric and ionospheric polarimetric mapping in auroral and polar regions (for solar-terrestrial-global-meteorological-interaction studies).

Detailed explanations will be provided in Sub-chapters II.3 and II.4.

II.3 SUGGESTIONS FOR PROGRAM RESTRUCTURING OF THE NATIONAL EFFORT IN ADVANCED RADAR POLARIMETRY

Advanced High-Resolution Radar Polarimetry has become of considerable importance not only to polarimetric seeker radar design, but also to other advanced high resolution radar modes, such as in tactical, surveillance, threat, crash avoidance, etc. operations. In concurrence with leaders in the overall polarimetric radar research effort within the m-to-submm wavelength region, it is evident that still a considerable amount of basic studies, data base updated measurements and base performance evaluations of existing polarimetric detection/identification/classification algorithms are required. Before a "final well-performing" prototype Polarimetric Radar Seeker can be implemented, we will have to fill-in the still prevailing gaps in basic theory, the design of well-performing polarization antenna polarization switches, filters, modulators and breadboard hardware technology. We will have to utilize the expanded polarimetric breadboard target and/or clutter bases and work on their continual improvement. One of the most urgent requirements for advancement is polarimetric vector signal processing which will require the mating of both advanced radar polarimetry and advanced detection estimation and modulation theory (e.g. 3 volumes of Van Trees), and come up with improved classification models making optimal use of polarization information, RCS matrix pulse doppler and/or FM-CW chirp, radar range ambiguity equations will have to be extended. Then, based upon realizable performance evaluations, will we finally be able to approach implementation of a high resolution polarimetric radar seeker in practice.

Therefore, it is logical to suggest the following plan for future polarimetric research activities.

PHASE I: ASSESSMENT OF AVAILABLE HIGH-RESOLUTION POLARIMETRIC IMAGING THEORIES/METROLOGIES/TECHNOLOGIES (Current phase of major national effort)

- PI.1 Identification of Radar/Target/Clutter Parameters for Optimum Design Approach:
- isolation of unresolved basic problems and initiation of required additional base studies.
- PI.2 Updating and Establishment of Metrological Data Base:
- identification of existing complete polarimetric measurement facilities (more or less non-existent for moving clutter analysis);
 - immediate acquisition of new complete broadband pulse-doppler/FM-CW polarimetric test-bed measurement facilities (government/industry/university).
- PI.3 Development of Modular Test-bed Radar Robotic Seeker Simulator:
- identify all ideal methods and design a non-realizable test system;

- identify the polarimetric vector signal processing techniques that must be developed for polarimetric radar robotic/automatic detection/classification/identification algorithm implementation.

PI.4 Initiation of Broadband Design Technology:

- identify all possible useful approaches available in base microprocessor/mm wave hardware design;
- identify antenna hardware design requirements.

PHASE II: DEVELOPMENT OF POLARIMETRIC RADAR-ROBOT-PROCESSORS
(Second phase only reached by a few of the top national efforts:
NO COMPLETE SOLUTION AVAILABLE AS OF TODAY)

PII.1 Completion of Theoretical Base Analyses and Radar Robotic/-Automated Detection, Estimation, Classification, Identification Algorithms:

- basic theory for anisotropic nonreciprocal target/clutter case;
- vector diffraction tomographic corrections;
- evaluation of polarimetric contrast optimization functions (H_0 , H_1 , H_2 , etc.).

PII.2 Processor Hardware Development:

- testing of best performing newly developed broadband polarization antennas with high polarization purity and sidelobe suppression;
- polarimetric modulator/filter/switching processor device perfection;
- polarization state adaptive agile systems development and priority testing.

PII.3 Algorithm Operation on Polarimetric Data Bases Recovered From Complete Polarimetric Measurements and/or Vector Scattering Model Generation:

- completion and comparison of metrological polarimetric data bases on a national interinstitutional basis (government/-industry/university);
- generation of reliable 3-D monostatic/bistatic polarimetric vector scattering model data basis obtained by any and all of the most advanced large computer processing systems (CRAY);
- generation of format of data files, storage input/output processing for most rapid data transfer.

P11.4 Realizable Performance Evaluation of Polarimetric High Resolution Radar Target Robotic Imaging Simulators:

- testing of any and all available approaches based on most advanced, not necessarily realistic models for designing the optimum polarimetric radar seeker simulator;
- compare and test FM-CW vs. pulse doppler polarimetric down-range/cross-range imaging radar classifiers/identifiers;
- develop prototype hardware modular test-bed polarimetric seeker radar systems so that a choice of optimal design for final prototype can be made;
- develop testing and performance evaluation methods.

PHASE III: SPECIAL PURPOSE BREADBOARD RADAR PROTOTYPE IMPLEMENTATION AND MANUFACTURE

(Third phase: only slightly touched by one or the other national efforts, however, STILL NO ONE HAS THE COMPLETE SOLUTION)

"Make dead-sure that none none of the essential tasks of Phases I and II are still open-ended/unresolved before engaging with full power into Phase III." . . . or else, your company may suddenly be out of competition.

II.3.1 Reorientation of the National Polarimetric Radar Research Effort

Due to my extensive interaction with other academic, industrial, and governmental research laboratories, it has become evident that there does exist a great need of increasing funding support for basic polarimetric radar research studies before engaging in the final design of polarimetric (seeker) radar systems. There still are many open problems to be resolved and there evidently does exist a great need of strengthening basic research efforts, particularly at universities in broadband high resolution radar polarimetry.

Therefore, we consider it useful to provide the following diagrammatic subsectioning chart on the "Advancement of Polarimetric Radar Technology" which we will use in the following as a guide for forwarding recommendations (Table 5).

What needs to be emphasized is the fact that in any and all of the national polarimetric radar research efforts, strong interaction among academic, industrial, and governmental research laboratories must be enforced. Certainly the funding level for basic thechnology must be increased, and all of us require highly improved measurement facilities. Here, we refer to our recent application in reply to DoD-URIP-FY 82: "8-12 GHz X-Band Frequency-Hop, Polarization-Adaptive Scattering Matrix Pulse-Doppler Radar Robotics System - A modular test-bed design of an advanced polarimetric radar system". We note that one such advanced high resolution polarimetric radar robotics facility ought to be made available for each of the spectral bands of interest in m-to-sub-mm-wave radar target handling in clutter.

TABLE 5: ADVANCEMENT OF POLARIMETRIC RADAR TECHNOLOGY

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National Forum of Experts

Appointed National Coordinator:

Government:

Industry:

Academia:

Workshops
Panel Discussions

BASIC TECHNOLOGY

Basic Polarimetry
Target Phenomenology
Clutter Analysis
Vector Inverse
Scattering
Target-Clutter
Interaction
Vector Imaging

METROLOGY

Basic Experimentation
Polarimetric Data
Collection
Radar Metrology
Ground Truth Metrology
Measurement Data Basic
Processing
Imaging Systems
(SAR/RAR/ISAR)

VECTOR SIGNAL/IMAGE
PROCESSING

Pulse Compression in
Radar Polarimetry
Polarimetric Doppler
Vector Signal Processing
Vector Image Processing
Algorithm Development:
Classification/
Identification

HARDWARE COMPONENT,
DEVELOPMENT & SYSTEMS
DESIGN

Electronic Hardware
Polarization Antennas
Polarization Transceiver
Pulse Doppler/FM-Chirp
Algorithm Robotics
Polarization Signature
Display

DEVELOPMENT OF MODULAR TEST-BED DESIGN OF BROADBAND HIGH RESOLUTION POLARIMETRIC COMPRESSION PULSE DOPPLER
RADAR SYSTEM: TESTING, COST-TRADE-OFF/TECHNOLOGY ANALYSIS

TECHNOLOGY TRANSFER TO INDUSTRY

II.4 IDENTIFICATION OF UNRESOLVED PROBLEMS AND FIELDS, DISCIPLINES OF APPLICATION

It is the prime objective to provide a succinct overview, logical subgrouping, and efficient ordering of unresolved problems identified. For meeting this objective, we have first identified the specific fields and disciplines in which advanced polarimetric high resolution radar robotics target imaging can be applied.

II.4.1 Fields and Disciplines of Application

The proposed research on advanced radar polarimetry will aid in ongoing investigations of pure theoretical/physical and applied nature relevant to a wide variety of fields in electromagnetic scattering and diffraction, geoelectromagnetic remote sensing and profile inversion in aeronomy. Here, we will attempt to categorize that list of identification of fields and disciplines in some more details.

II.4.1.1 Basic Polarization Vector Target Signal Analysis

For the purpose of advancing basic vector diffraction and scattering theory, we require urgently additional basic electromagnetic polarimetric signature (theoretical, metrological) studies of specifically selected classes of symmetrical, asymmetrical, reciprocal and anisotropic scatterers - in isolation, homogeneous, and mixed heterogeneous distribution for the support of analytic model simulation studies of target and/or clutter:

- basic inverse/direct scattering and diffraction;
- basic monostatic and/or bistatic radar target phenomenology
- basic scattering matrix measurement theory
- basic polarimetric radar metrology
- basic numerical target modeling theory
- basic vector/tensor radiative transfer theory
- propagation and imaging through inhomogeneous media

II.4.1.2 Radio-to-mm-Wave Propagation Through Turbulent, Heterogeneous Media

Whenever the wavelength becomes comparable to the characteristic eddy and/or particular scatterer sizes in the propagation media, multiple scattering and, therefore, depolarization effects on the wave interrogating polarization vector state cannot be neglected and basic principles of radar polarimetry apply:

- design of frequency-reuse dual polarization propagation links (e.g. earth-satellite; line-of-sight coast-to-coast; beyond the horizon imaging radar);
- electromagnetic wave propagation assessment for atmospheric propagation paths (ducting along marine ocean boundary layer, ducting over desert region, ray path bending problems, mirages, etc.);
- description of atmospheric, tropospheric eddies.

II.4.1.3 Monostatic and Bistatic Radar target Handling: The Radar Target Detection, Classification, Imaging, and Identification Problem

One of the most important defense applications of advanced radar polarimetry is the detection of targets embedded in clutter, target vs. clutter discrimination, target classification, target in clutter imaging, target robotic identification - one of the central issues of this research.

II.4.1.4 High Resolution Pattern Image Analysis in SAR/RAR/ISAR Robotic Imaging Systems

It was shown that the reconstruction of the SAR image with optimum feature quality requires basic knowledge of the optimal target/clutter polarization vector null theory (Kennaugh) which can effectively be applied to increase image quality, resolution, and allow robotic polarimetric image pattern analysis:

- basic technology of SAR/RAR/ISAR polarimetric image formation;
- polarimetric image pattern analysis;
- polarimetric matched filter image clutter suppression;
- polarimetric identification of man-made target images vs. natural images.

II.4.1.5 Air and Sea Traffic Control Applications

A combined polarimetric compression pulse doppler radar mode of operation should allow the detection, identification, and the imaging of atmospheric turbulence, high moisture wind shear and its density flow/velocity profile descriptions, as well as the mapping of electric storm effects:

- instantaneous detection of dynamic changes of generalized vector of target motion;
- air/sea traffic flow at airports/harbors;
- aircraft take-off and landing operations;
- sea-vessel docking maneuvers;
- early detection of strong otherwise undetectable wind shear close to ground (1982 Louisiana/New Orleans Airport disaster).

II.4.1.6 Polarimetric Compression Pulse Doppler Radar Meteorology

In our recent studies on basics of polarimetric radar meteorology, we have clearly established that the optimal scatter polarization vector null theory and its various time-averaged and partially coherent presentations are directly applicable to the entire complex field of radar meteorology. Particularly, we have now shown how to advance the theory and metrology of cloud-

microphysics, electric storm dynamic cloud changing aspects, the micro-study of dynamic hydrometeor states within the radar classification and identification of dynamic precipitation states such as hail, rain and snow, wind shear detection and tornado cyclone vortex motion description:

- basic theory & metrology of cloud microphysics;
- basic theory & metrology of atmospheric electricity;
- basic theory & metrology of severe storm detection, imaging, classification and identification;
- metrology and description of severe wind shear bursts;
- complete electromagnetic description of the atmosphere of planets, in particular, Earth, the dust storms on Mars, Venus, the Moon, Io of Jupiter, the Saturn rings, etc.;
- general space and meteorological metrology.

II.4.1.7 Remote Sensing of the Atmosphere, Rough Surfaces, Intense Sea States, and Vegetation Scatter

It has now been well established that rough surface, plus volumetric underburden, sea and vegetation scatter, show very distinctive polarimetric broadband signatures which should be of great importance to agricultural, forestial, geophysical and naval-oceanic remote sensing:

- broadband polarimetric signatures of geophysical rough surfaces, ocean marine states, coastal geophysical formations, agricultural, forestial and fisheries remote sensing;
- polarimetric pattern recognition in remote sensing;
- polarimetric pattern identification of specific signatures of sea, rough surface, vegetation scatter;
- micro-scattering cell analysis in remote sensing.

II.4.1.8 Mesospheric, Ionospheric, Magnetospheric Mapping in Auroral and Polar Regions

Our polarimetric radar research should be of utmost relevance to analyzing dynamic scattering from mesospheric/ionospheric/magnetospheric auroral plasma and the Advanced High Resolution Polarimetric Radar System should be of great use to study the internal structure of mesospheric/ionospheric/magnetospheric current discharge effects in studies of solar-terrestrial interactions:

- polarimetric signatures of mesospheric/ionospheric/magnetospheric current discharge and auroral effects within boreal and austral auroral belts;
- mapping of mesospheric/ionospheric/magnetospheric properties at low altitudes within the auroral belts and in the auroral oval.

II.4.1.9 Polarimetric Robotic Imaging Radar Remote Sensing in Aeronautical and Space Research

Without any doubt in future aeronautical and space exploration, the most sophisticated, advanced high resolution broadband polarimetric compression pulse radar robotic imaging systems will have to be used to find the "needle in the haystack", i.e., to be able to detect with forefront high technology

sensor systems, electromagnetically camouflaged objects of galactical and/or artificially-created objects. To do so, the entire usage of the imaging capabilities of the interrogating electromagnetic wave will have to be accomplished in order to utilize its fundamental robotic imaging capabilities through the concept of its polarization-sensitive, scatterer feature temporal and spatial resonance matched vector signal filtering and image pattern recognition modes of operation:

- detection of unusual planetary surface, atmospheric-to-ionospheric characteristics whenever applicable;
- interpretation of microphysics of planetary core, moon rings, etc., comets and other planetaric and galactic debris;
- planetary remote sensing (II.4.1.6);
- detection of extra-terrestrial voyagers if ever approaching our planetary system (preparation for the advanced galactical warfare of the not too distant future!).

II.4.1.10 Summary of Applications

It was the objective to widen our scope of possible applications of the new highly interdisciplinary science and technology of "HIGH RESOLUTION BROAD-BAND COMPRESSION PULSE DOPPLER POLARIMETRIC RADAR ROBOTIC IMAGING". Certainly, sooner or later, this advanced high technology will create the basis for aeronautical and space remote sensing in a galactic sense. Hitherto and currently, it must be our aim to bring about the required reorientation of the National R/D/M effort to accomplish this goal of achievement of the "Nineteen-Nineties", by which time we will most likely approach our next "FIX-STAR" system.

Now, before we can turn our minds loose on these inspiring problems, we need to readdress many fundamental problems which still have not been solved, but must be resolved within the next five to ten years.

II.4.2 Basic Direct & Inverse Vector Diffraction and Scattering Theory

The Gateway to Advanced Radar Polarimetry is a solid, broad and, at times, very deep understanding of basic direct and inverse VECTOR DIFFRACTION and SCATTERING theory without which polarimetric radar target phenomenology cannot be comprehended. For the past twenty years, the research objectives of the research director and his senior research consulting staff was to promote this highly demanding (mathematics, physics, signal processing, metrology, pattern robotic image analysis), time-consuming research efforts of advancing High Resolution Radar Polarimetry.

Here, we wish to draw our attention to a number of unresolved basic problems in direct and inverse vector diffraction/scattering theory which will require our renewed and continual attention for many years and decades to come before all ends and corners of High Resolution Radar Polarimetry have been sewn together (see Proceedings NATO-ARW-IMEI-1983; Chief Editor: W-M. Boerner, 1984).

II.4.2.1 Promotion of the New Mathematical-Physical Disciplines of

"GENERAL PROFILE INVERSION"

As was most recently well-defined by Sabatier (1983-84), Inverse Scattering is not a New Technology to solve profile inversion problems or provide new machines for remote sensing, geophysical sounding, etc. NO, it is and may as well be accepted as a new interdisciplinary scientific discipline based squarely on mathematical theories of matrix inversion and that of integral and integral-differential equations, methods of regularization, etc., and dealing with the basic physics of the wave interrogating medium and target nature for the purpose of recovering the unknown to be specified target features from metrological data. Hence, in essence, it is a mathematical-physical aid in solving general profile inversion problems. The problem of radar target handling using advanced polarimetric high resolution broadband compression pulse radar robotic imaging modes will draw heavily from this new discipline and, therefore, we need to keep up with the state-of-the-art of "GENERAL PROFILE INVERSION" at all times. We will keep up with the literature, attend, plan and execute, advanced research workshops/seminars and isolate any useful methods for advancing the problem of detecting, classifying, imaging and identifying radar targets embedded in clutter.

II.4.2.2 Identification of Unresolved Problems in Direct Vector

Diffraction/Scattering Theory

Because of the fact that polarimetric effects cannot be neglected, we deal, in general, with a vector scattering/diffraction problem in radar polarimetry. However, most of the mathematical inverse methods are scalar approaches and, thus, great need exists to develop improved vector diffraction and vector scattering theories from which inversion techniques can then be derived. (IEEE Trans-AP 29(2), March 1981, Special Issue on Inverse Methods in Electromagnetics; Proceedings NATO-ARW-IMEI-1983, D. Reidel Publishing Co., Dordrecht, Holland, 1984)

II.4.2.3 The Minkowski-Hurwitz-Christoffel Inverse Methods of Differential Geometry

In the inverse scattering problem of reconstructing the shape of a 3-dimensional, close convex-shaped surface of a target from polarimetric radar measurements, the Minkowski-Hurwitz-Christoffel inverse theory of differential geometry is central to solving this complicated problem. Our research team has contributed profoundly to advancing this problem, i.e., providing the first order correction term to physical optics inverse scattering techniques. We are collaborating with Prof. S.K. Chaudhuri, Dr. A.G. Ramm, Kansas University, and B. Borden, Naval Weapons Center, on this research topic, in continuation of Foo's and Ho's M.Sc. Theses (Foo, Ph.D. Thesis; Ho, Ph.D. Thesis topic).

II.4.2.4 Fock Function Analysis of Diffraction Effects in the Pen-Umbra Region of a Closed Convex-Shaped Scatterer

One of the great shortcomings of most radar target shape imaging methods is the fact that those are derived from the physical optics approximation (Kennaugh's transient ramp response method), in which only the illuminated region contributes to the backscattered field. What is urgently required is a thorough analysis on improving the existing inverse scattering theories by introducing the second order correction to physical optics inverse scattering which strongly depends on a Fock function analysis.

II.4.2.5 Extension of the Concept of Electromagnetic Inverse Boundary Conditions Leading to Vector Holography for Reconstruction of the Shape and the Material Properties of Closed Finite and/or Perfectly Conducting Targets

Our research team was actively involved in introducing this concept of "inverse boundary conditions", which are boundary conditions not containing the knowledge of the locus of interface (surface) and of the local surface impedance properties of such a target, but given the complex electric and the complex magnetic field everywhere in its neighborhood, allow to recover the unknown surface locus and its associated local surface impedance from the knowledge of these fields. The interesting concept of locally necessary, but not sufficient, yet globally necessary and sufficient conditions was introduced in (Boerner and Ahluwalia, Can. J. Phys., 50(23), 1972, pp. 3023-3061; Ahluwalia and Boerner, IEEE, Trans AP-21(5), pp. 663-672, 1973/AP-22(5), pp. 673-682, 1974).

With the advent of compact near-field to far-field/far-field to near-field measurement ranges, we are now able to verify these concepts in more detail.

II.4.2.6 Target Polarization Vector Scattering Center Theory

In analyzing the intra-target scattering mechanism in radar polarimetry, the scalar G.O. optics approaches are highly insufficient, and a vector scattering center intra-target interaction theory is required. In consultation with members of the ElectroScience Laboratory/OSU (Kennaugh, Burnside, Moffatt, Young, Richmond), and former members of Sperry Research Center (Bennett, Barnes, Mieras), we are in the process of formulating such a theory which is of fundamental relevance to polarimetric down-range target imaging/classification/identification.

II.4.2.7 Basic Radar Clutter Descriptive Theory

One specific sub-field of vector scattering theory in which still many open problems exist is that of polarimetric clutter scattering, whereby clutter describes an interactive ensemble of closely packed (in wavelengths) scattering centers which may be at rest and/or partially are in motion. Very recently, there have been some excellent results obtained using the polarimetric radiative transfer theory combined with Bragg's diffractive, and other coherent multi-scattering theories (Fung, Ishimaru, Beran, Leader, etc.), which now require systematic application to specific clutter models. In particular, the advancement of the statistical optimal polarization clutter null (mean, and variance/spread) is urgently required in further advancing theory and methods of target discrimination from clutter, etc.

Currently, we are developing a unified theory on even/odd bounce multiple vector scattering theory which promises to be of great use in separating useful target signals originating from metallic man-made objects from heterogeneous material and vegetational clutter.

II.4.2.8 Basic Target and Clutter Phenomenology

Related with the above inverse scattering problems is that of uniquely describing the monostatic, as well as bistatic vector scattering properties of isolated and distributed targets (clutter). Based upon Kennaugh's monostatic target-description, we are well advancing in extending this theory to the general anisotropic monostatic and general nonreciprocal bistatic case.

It will be of particular interest to apply group theoretic approaches to both the monostatic and bistatic cases of varying degrees of target symmetries. In a next step, we require to find a unique set of target characteristic identifiers for the bistatic case, similar to the five independent target descriptive parameters defined first by Kennaugh, and then illuminated in greater detail by Huynen for the monostatic reciprocal case, which is currently being investigated by us in continuation of the collaboration with the late Prof. Edward M. Kennaugh.

II.4.3 Base Technology Support

In continuation of the respective section in Part II.1 (Section II.3) the following lists some of the most important problems which need to be further developed immediately.

II.4.3.1 Basic Radar Target Polarimetry

There still exist several gaps before the unique, closed theory is established (M. Davidovitz, M.Sc. Thesis, "Extension of Kennaugh's Optimal Polarization Null Theory ..."), and we require the reactivation of the initiating polarimetric research expert base to fill the gaps. We are fortunate to have Dr. David L. Moffatt, Prof. Georges A. Deschamps, Dr. J. Richard Huynen, and Prof. Yuen-T. Lo among our external collaborators.

II.4.3.2 Polarimetric Radar Target Handling

We understand the target optimal polarization null theory rather well for the case of symmetric reciprocal targets (Huynen's Thesis); but for the more general anisotropic, non-reciprocal case (Davidovitz's Thesis), an interpretation in terms of target rotation invariant parameters was not available. We are fortunate to have Dr. David L. Moffatt, Dr. C. Leonard Bennett, Dr. J. Richard Huynen, and Prof. Georges A. Deschamps join us in attacking the still prevailing problems, together with all of our research graduate assistants.

II.4.3.3 Polarimetric Clutter Analysis

Although Huynen's N-target decomposition theory presents a milestone in radar target description, it has not led to practical implementation for polarimetric clutter description. We require instead, a coherency matrix approach for the general anisotropic, non-reciprocal case which still needs to be developed (Nespor's M.Sc. Thesis) incorporating the even/odd multi-bounce scatter center interaction theory so that the mean optimal polarization null loci and its spread functions can be determined. We are fortunate to have good contacts with polarimetric radar meteorologists such as Dr. E.A. Mueller, Mr. A.L. Hansen, Dr. R. Larson, Dr. N.C. Mathur, Dr. D. Stock, Dr. G.C. McCormick, Dr. M. Thiel, Dr. J.K. Huynen, and Dr. A.J. Poelman; all being engaged in detailed electromagnetic clutter analyses.

II.4.3.4 Polarization Antenna Theory

We have attracted one of the foremost polarimetric antenna design theoreticians, designer and builder in Prof. Yuen-Tze Lo, whose deep practical understanding of the electromagnetic polarization properties of matter are rarely matched. It will be a strong plus to have Prof. Yuen-Tze Lo join our efforts as external consultant within the University of Illinois at large.

In addition, this effort is strengthened by the engineering expertise of Arthur L. Hansen, former Director of NEXRAD, Dr. Eugene A. Mueller, the

scientific manager of the CHILL radar system and by Dr. Rudolf Wohlleben, Chief of Antenna Division, MPI-Radioastronomy, who have contributed considerably to polarimetric antenna design.

II.4.3.5 Polarimetric Down-Range/Cross-Range Imaging

Although "scalar" down-range/cross-range imaging techniques have existed for many years, our CL-EECS-UIC team effort is certainly the strongest in the field, able to disprove former claims of disclaiming polarization information, and withstanding such professional purgery and scientific insult (Here, we refer to the sad, non-scientific behavior of the two so-called expert consultants during the June 1983 NAV-AIR Electronics Contract Review Meeting at the Naval Research Laboratory in Washington, D.C.) The principal investigator was the invited senior guest editor of IEEE Transactions on Antenna & Propagation, Vol. 29(2), March 1981, pp. 185-417; he has been invited and was selected to be the director of one of the most important contributions to electromagnetic imaging hitherto, the NATO Advanced Research Workshop on "Inverse Methods in Electromagnetic Imaging", Sept. 18-24, 1983. It was/is the prime objective in these research promoting efforts to advance polarimetric down-range/cross-range mapping and two/three dimensional target imaging. We have access to the widest and most prominent expert bank available, within NATO member countries, which has agreed to serve in a consulting effort. We will be making use of these expert resources during our upcoming DoD research efforts.

II.4.3.6 Polarimetric Remote Sensing Through Inhomogeneous, Anisotropic Media: Vector Diffraction Tomography

We have contributed profoundly to advancing this still unresolved field of electromagnetic imaging through a heterogeneous, discontinuous medium as the radar target environment in the mm-wavelength region indeed is. We have collected the foremost researchers in this field such as Dr. A.J. Devaney, the late Prof. E.M. Kennaugh, Dr. A. Ishimaru, Dr. C.L. Bennett, Prof. A. Kac, Prof. K.J. Langenberg, Dr. M. Pfeiler, Dr. M. Kaveh, and Prof. Alan Anderson, who all are in continuous deep discussions with us on advancing vector propagation tomography.

II.4.3.7 Conclusions

We would be able to identify here several more problems which we would be able to solve, however, the set of problems outlined above should be exemplary.

II.4.4 Base Metrology

II.4.4.1 Our Application for an Advanced Polarimetric Radar System in Reply to DoD URIP-FY 83

In pursuing the design of the most flexible modular test-bed broadband polarimetric radar system, we have obtained responses from the widest spectrum of competent polarimetric radar metrologists that presently could be assembled. Therefore, we refer to our reply to the DoD-URIP-FY 83, which is entitled

"8-12 GHz X-Band Frequency-Hop, Polarization-Adaptive Scattering Matrix Pulse-Doppler Radar Robotics System - A Modular Test-Bed Design of an Advanced Polarimetric Radar System",

and to the

"SPC Technical Proposal 820-380, Advanced Polarimetric Radar Proposal"

for further details. We have already been engaging in detailed planning for basic measurements to be carried out with such a radar system and a major descriptive measurement proposal package will be forthcoming. At this time, we refer to the detailed outlines of above applications.

II.4.4.2 Verification of the Metrological Applicability of the Modular Test-Bed Polarimetric Transceiver System Designed in II.3.

Mr. Robert Lempkowski will carry out the electronic hardware construction under the supervision of Mueller/Hansen/Boerner, in continuation of his M.Sc. Thesis (complete polarimetric, modular test-bed design of a high resolution radar system). He will be building and testing the system as a PhD. Thesis project on the UIC-SEL building's roof-top radar range.

II.4.4.3 Derivation of Optimal Polarization Ellipse Sweeping Algorithms for Polarimetric Transceiver Systems

Based on the preliminary analysis of Poelman, we will be generating an automated transmit/receive antenna polarization state sweeping algorithm, taking metrological clutter/target discrimination aspects into consideration. The work will be carried out with the input of A.J. Poelman and A.L. Hansen, utilizing the expertise developed by Benjamin Beker and Marat Davidovitz in antenna polarization state handling.

II.4.4.4 Evaluation of Polarimetric Measurement Data and Design of Useful Polarimetric Reference Targets

Measurements on complete scattering matrix returns for simple to increasingly more complex shapes will be carried out on the Teledyne-Micronetics Measurement Range in collaboration with NAV-AIR (6.2), NAV-SEA (6.2), and at the ESL-OSU indoor compact RCS Range in collaboration with Dr. Jonathan D. Young, Dr. Otto Kessler (NADC), Dr. J. Richard Huynen, and three graduate research assistants, will be involved in these measurement campaigns.

We wish also to invite all members of the industrial polarimetric seeker radar efforts to join us in this effort and make available data from their own measurement range.

A considerable part of this task will be concerned with the proper design of reference test targets and "reference test clutter".

II.4.4.5 Polarimetric Bistatic Clutter Measurements

In collaboration with ERIM (Mr. Richard Larson, Dr. Demetrios Politis, etc.), we will be engaging in bistatic complete polarimetric target plus clutter, and clutter only measurements for the purpose of verifying the bistatic vector scattering theory developed by Mr. M. Davidovitz in his M.Sc. Thesis. This metrological base research effort will be very important for the analysis of the non-reciprocal scattering matrix case and essential for target detection in an anisotropic clutter environment. We consider it essential that the National Polarimetric Radar Seeker Effort join into this important metrological campaign.

II.4.4.6 Measurement Data Acquisition for Polarimetric Clutter Analysis
Comparing various clutter descriptive methods such as the Huynen N-target decomposition theory, the Huynen target invariant rotation angle approach, and the N-bounce vector scattering center interaction theory, we require reliable measurement data similar to Teledyne Micronetics data. This research will be carried out with strong interaction of ERIM, ESL-OSU, ISWS-UIUC, and two postgraduate student assistants, hopefully with our own advanced polarimetric radar system, which will sooner or later, be established at Glenview Naval Air Station, Glenview, Illinois.

II.4.4.7 Development of Polarization Vector Signal Optimal Target vs. Clutter Contrast Merit Functions

In this research, we will be analyzing novel principles of detection, estimation and classification theory (Van Trees, Vols. 1 to 3), as well as Kennaugh/Kozlov/Huynen/Poelman/Ionnidis-Hammers/Vannicola's polarimetric contrast optimization algorithms (Demirbos 1984). The research will be carried out in collaboration with Drs. D.L. Moffatt, A.J. Poelman and Mr. V. C. Vannicola with the assistance of one or two postgraduate research assistants.

II.4.5 Polarization Vector Signal, Image Processing

Great emphasis was placed in Section II.1 and II.3. on this aspect of the polarimetric radar problem.

II.4.5.1 Optimization of Target vs. Clutter Contrast Classification Merit Functions

Extensive treatise exist on scalar target detection, estimation, classification and identification theory and techniques (e.g. Van Trees, Vols. 1-3); however, there really does not exist a systematic combined approach of mating the above methods with polarization vector signal processing except for the outlines provided in (Proceedings of the NATO-ARW-IMEI-1983). The existing polarimetric contrast, estimation theories developed by Kennaugh, Kozlov, Ioannidis/Hammers, Zhivotovsky, and Vannicola merely present a first step in the proper direction (see II.3). However, we do have the expertise gathered to get at this most complicated, advanced target/clutter contrast separation problem as, i.e., V.C. Vannicola, S.M. Elnoubi, G.A. Deschamps, J.R. Huynen, A.J. Poelman, T. Sarkar, K. Demirbas, and R.M. Bevensee.

II.4.5.2 Polarimetric Radar Pattern Recognition Algorithm Design

Methods of image and picture processing have been advanced very strongly during the past decade. However, little was done to apply these methods systematically to algorithm development for pattern recognition in polarimetric vector signal and vector image processing. In collaboration with FHP-FGAN (Gniss and Magura), we are in the process of setting up a very strong research effort in this new, exciting field of high resolution polarimetric radar imaging.

II.4.5.3 Radar Target Classification Based on Multi-Frequency Optimal Polarization Matched Filter Design

Using the target polarization null signatures for multi-frequency data which allow a target downrange resolution along line-of-sight of the order of the wavelength promises to provide sufficient information for developing reliable target classification algorithms. Various approaches (see Sections II.1 and II.3) are currently under investigation in collaboration with O. Kessler, J.R. Huynen, V. Nalbandian, and are carried out by B-Y. Foo, A.C. Manson, B. Beker and A. Agrawal.

II.4.5.4 Development of Color-Graphic Joy-Stick Operated Multi-Notch Polarization Matched Filter Design

In collaboration with A. Poelman, various approaches of developing special purpose mini-computer software (and hardware) for polarization-matched clutter suppression filters are being considered (NATO-IMOR Fellowship) as outlined in II.1 and II.2.

II.4.5.5 Development of High-Resolution Polarimetric Down-Range (Scatter matrix) and Cross-Range (ISAR) Target Imaging Algorithms

We have been engaged in basic research studies on this subject matter during the past fifteen years, and using principles of tomographic projection theory have developed various image reconstruction algorithms. It is our intent to expand on this research utilizing our new DEC-VAX 11/750-11/780 Research Computer Processing Facilities (see Chapter VI).

II.4.5.6 Polarimetric Image Feature/Pattern Manipulation of SAR/RAR Images Complete polarimetric image reconstruction according to the span-invariant

$$|S_{opt}|^2 = \text{Span} \{[S]\} = |S_{AA}|^2 + |S_{AB}|^2 + |S_{BA}|^2 + |S_{BB}|^2 = \text{invariant}$$

is considered using cross-range signatures, as for example, that available from polarimetric SAR/RAR imaging, or microwave holographic testbed measurement setups (FGAN/FHP, West Germany).

II.4.6 Computer Numerical Data Crunching and Target/Clutter Model Simulation

Because we have just begun initiating this process of developing the computer-numerical programs, only brief headings are presented here:

- (1) Near-field-to-far-field inverse scattering/transformations using spherical vector wave function expansions (H.P.S. Ahluwalia with update by D. Hess and P.F. Wacker).
- (2) Stokes vector manipulations on the Poincare polarization sphere and manipulations on polarization polar rectangular, elliptical, etc., projective maps (X.-Q. Huang with updates from J.C. Daley, L.A. Morgan, C.L. Bennett, R. Raven, F. Sedenquist and others).
- (3) Advanced numerical moment-method programs for calculating RCS matrix data for simple symmetrical and asymmetrical shapes (S. Saatchi with L. Henderson, J. Richmond, R.E. Harrington, A. Taflove, C.L. Bennett, and others).
- (4) Polarimetric data processing algorithms developed within EMID-CL-UIC (S. Saatchi, M.B. El-Arini, A.C. Manson, B-Y. Foo, J.D. Nespor, et al with J. Daley, S. Weisbrod, L.A. Morgan, O. Kessler, and others).
- (5) Fast-Fourier transform for Radon-Fourier transform projection/propagation/diffraction tomographic imaging (C-W. Yang, B. James, A.C. Manson with A.J. Devaney, M. Kaveh, H. Ermert, and others).
- (6) Polarimetric multi-notch matched filter clutter suppression program (A.C. Manson with A.J. Poelman).

- (7) Polarimetric radiative transfer clutter modeling program (A.P. Agrawal, A. Khounsari with A.K. Fung, A.J. Blanchard and A. Ishimaru).
- (8) Bistatic optimal null modeling programs using bistatic scattering matrix modeling data (M. Davidovitz, S. Saatchi, A.C. Manson with J.D. Young, R. Larson, and others).
- (9) Polarimetric (even/odd) N-bounce clutter simulation program (N.C. Mathur, H. Khan, A.C. Manson with F. Sedenquist, C.L. Bennett, and others).
- (10) Measurement data filing, handling program (new development by A.C. Manson, J.D. Nespor with E. Walton, L. Henderson, D. Morgan, and others).
- (11) Vector signal processing algorithms for target enhancement/clutter suppression (C-Y. Chan, B. Beker, A. Belkin, A.C. Manson with E.M. Kennaugh, V.C. Vannicola, and others).
- (12) Vector signal image processing algorithms for polarimetric RAR/SAR/ISAR image manipulation utilizing advanced schemes of N-Dim vector pattern recognition (A.C. Manson, B. James with S.M. Elnoubi and others).

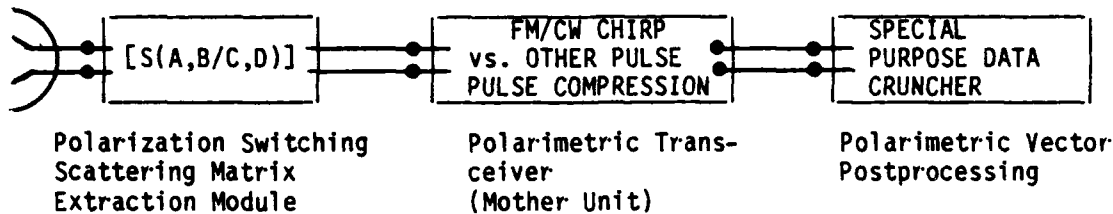
We are in the process of working out efficient and easily accessible, yet securely encoded filing systems. Time permitting, the entire office, reports and theses paper processing operation will be transferred to the newly acquired DEC-MATE I system which should make our operation even more sufficient.

II.4.7 Polarimetric Hardware Development

II.4.7.1 In-House CL-EECS-UIC Generation of Special Purpose Radar Test-Bed Measurement Facility Using Modular Polarimetric (Scattering Matrix) Transceiver Design

We have painstakingly hammered down the fact that the most essential component of the final breadboard polarimetric radar seeker system will be its polarimetric antenna/transceiver system. We have been shopping around and are investigating what other competitors' polarimetric radar seeker efforts are doing, resulting in the following recommendations:

Modular Test-Bed Requirements: With the aim of figuring out which specific polarimetric system may serve the final product requirements best, design a universal modular transceiver system as the mother unit onto which various different polarimetric antenna plus scattering matrix preprocessing modular units can be attached, exchanged and compared in their performance capabilities.



Polarimetric Modular Radar Seeker Test-Bed: The following complete coherent phase-locking amplitude plus complete phase polarization antenna/transceiver configurations should be tested and for each configuration the required modular unit should be built in a "block world approach".

Combinations of Modular Design Antenna Polarization State Bases

TRANSMIT	RECEIVE	EXTRACT
H, V linear	H, V linear	[S(H,V)]
L, R circular	L, R circular	[S(L,R)]
H, V mixed	L, R	[S(H,V)], [S(L,R)]
L, R mixed	H, V	[S(L,R)], [S(H,V)]
A, B general	A, B general	[S(A,B)]
A, B general mixed	C, D general	[S(A,B)], [S(C,D)]

Note, the symbols A, B and C, D are to denote any arbitrary orthogonal polarization vector pairs on the polarization sphere.

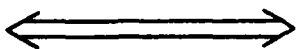
Polarimetric Transceiver "Mother" Unit: For each of the identified pulse compression techniques chosen for possible implementation in the final polarimetric special purpose radar system, a modular mother transceiver unit is to be built. Since we have not been able to obtain all of the basic information due to classification/competition propriety, we will not provide any detailed recommendations at this time. However, we have made positive contacts with expert design engineers in FM-CW chirp, CW scatterometric and multifrequency pulse doppler radar design, who are interested in assisting our efforts of rapidly advancing this specific state-of-technology.

Concluding our recommendations on setting up the base metrological polarimetric special purpose radar modular test-bed facility, as had been emphasized repeatedly during the preparations of this final report, we state:

"There still does not exist the final solution anywhere for the proper design of a functional special purpose polarimetric radar system which could be implemented in practice".

Therefore, it is of paramount importance for the survival of the national polarimetric radar seeker R/D/M effort to acquire such in-house base metrological modular test-bed polarimetric radar facilities. Since no one has the optimal answer, let us find it by having the in-house base facility for testing and weighing one possible approach against the other. The weighing, testing, sorting and optimizing of one approach against the other must include the entire wave target interrogation capabilities of the electromagnetic wave, i.e., we are dealing with a

FREQUENCY/DISPERSION/
AMPLITUDE/GAIN PHASE/
DOPPLER POLARIZATION/
GEOMETRY



"POLARIZATION-SENSITIVE
TARGET FEATURE/MATERIAL
DECOMPOSITION TEMPORAL
& SPATIAL RESONANCE
PHENOMENON"

Thus, we must optimize polarization against doppler, down-range/cross-range high resolution imaging methods, and vice versa. To be able to come up with a "dead proof" final solution, we require the modular test-bed design facilities described above, and, in particular, the advanced polarimetric radar system applied for in our reply to DoD-URIP-FY 83 must be implemented in the near future.

II.4.7.2 Design of Improved Polarization Antennas with High Polarization Purity and Strong Sidelobe Suppression

The polarimetric antenna systems currently available (from the shelf) are far below what is required and that can be achieved. We will commission one of the most famed polarization antenna designers, Prof. Yuen-Tze Lo, to join in our research together with Dr. R. Wohlleben and with the assistance of two postgraduate research assistants, Mr. Benjamin Beker and Mr. David Schultz, who are interested in pursuing this polarimetric antenna design research in their doctoral research treatises.

II.4.7.3 Design of Improved Polarization Switches with High Polarization Purity and Fast Switching Times

In coordination with Electromagnetic Sciences, Inc. and Mr. Arthur L. Hansen, we are considering design alternatives for constructing improved high PRF polarization switches of high polarization purity using pin-diode techniques. This research will be carried out by Mr. Kenneth J. Genutis for the completion of his M.Sc. graduate research effort.

II.4.7.4 Development of Dynamic Polarization Fork Indicator Polar Screens

Provided with the design specifications of Mr. Andre J. Poelman, we will be developing our own polarimetric radar robotics facilities with the assistance of D.L. Moffatt, J.R. Huynen, A.J. Poelman, and with graduate research assistant Mr. Robert Lempkowski (Ph.D. Thesis topic).

The development of this important polarimetric radar robotics simulator equipment is essential for further advancement in basic and applied radar polarimetry.

II.4.7.5 Development of an Advanced Meteorological Polarimetric Pulse-Doppler Radar Facility

In close collaboration with Dr. E.A. Mueller, Illinois State Water Survey, Meteorology Division, and Dr. A. Schroth, DFVLR-OPH, we are in the process of designing experiments for mating the existing CHIL/DFVLR radars and our "advanced polarimetric radar system" for purposes of assisting basic research in cloud microphysics shear-wind analyses, and the imaging and characterization of overall cloud properties (M.Sc./Ph.D. Theses of J.D. Nespor and A.P. Agrawal).

II.4.7.6 Development of a Polarimetric Hostile Environment Target-Plus-Clutter Simulator

Using our DEC-VAX 11/750-780 research computer processing facility, it is one of our most important long-term projects to build up a library on "far-field-to-near-field target-plus-clutter electromagnetic vector field" model programs, which are to simulate, as close as possible, realistic geo-electromagnetic environments, such as those encountered in polarimetric tactical radar interaction. This research will be co-coordinated with that of Drs. F. Sedenquist and R. Russel of MI-COM, DRSME-REG. Given this data library bank, we then will be able to verify various target detection, classification, imaging, and identification algorithms developed in our laboratory and elsewhere (Ph.D Theses of A.C. Manson, X-Q. Huang, S-M. Huang, C-M. Ko).

II.4.8 Concluding Remarks

During the NATO-ARW-IMEI, Inverse Methods in Electromagnetic Imaging, Bad Windsheim, FRG, Sept. 18-24, 1983, a special session on polarimetric metrology and one workshop group were assigned to analyze precisely which kind of polarimetric metrology approaches are to be taken and how useful data banks could be exchanged (see Proceedings, NATO-ARW-IMEI-1983, Part 6, Paper #VI.7).

II.5 TIMELINESS, RELEVANCE AND BENEFITS OF NEW TECHNOLOGY

II.5.1 Timeliness and Relevance

Attempts on utilizing advanced concepts of radar polarimetry in radar target detection, classification, imaging, and/or identification have been made sporadically during the past three decades; and many enthusiastic attempts, e.g. such as by Kennaugh, Copeland, Gent, Huynen, Long and others, have been abandoned. It is only since the recent persistent, renewed drives of Lloyd W. Root of MICOM and André J. Poelman of SHAPE-TC, that radar polarimetry is gaining credibility of success, specifically, with promising polarimetric seeker radar designs pursued at Martin-Marietta, Bendix, Boeing, Honeywell, THORN-EMI, Thompson CSF, Telefunken, etc., and also within our research laboratory at EMID-CL-EECS-UIC.

The main reasons for success are fourfold:

- (i) polarimetric antenna and polarization state switching theory and technology have been advanced very considerably during the past few years, although we still have to improve polarization isolation, cancellation and sidelobe suppression by many dBs;
- (ii) high resolution downrange and crossrange imaging have proven to be highly polarization sensitive, i.e., implementation of increased complete polarimetric scattering matrix facility may result in reduction of very costly array image processors. A trade-off between broadbandness, doppler and polarimetric completeness is possible;
- (iii) polarimetric radar theory is still not complete; and with the contributions of our research group and that of our collaborating research teams at ERIM, ESL-OSU and at SHAPE-TC, we have introduced some very important novel features which make broadband polarimetric pulse doppler and FM/CW down/cross range imaging an indispensable tool in high resolution target imaging and allows separation of weak target signals in strong clutter;
- (iv) the rapid, continuing advances of high-speed microprocessor ICS chip systems allow real-time computations of large bulk data such as will be obtained in high resolution, complete polarimetric radar systems, and thus make Radar Polarimetry an indispensable realistic tool in "smart seeker", or completely automated Robotic Imaging Radar Systems.

Therefore, to analyze the complete impact polarimetric radar theory and technology definitely have on modern high-speed, automated radar robotics, this research effort should be considered a PILOT PROJECT providing leadership in the field.

II.5.2 Quality and Increased Productivity.

Only if a critical mass of competent research staff, research student population, and sufficient funding is obtained, will new results be produced in a complex, highly multidisciplinary, interinstitutional research field as radar polarimetry proves to be. We have put together at Polarimetrics Incorporated and at UIC-EECS-CL-EMID, very effective research teams. The number of excellent research papers, from purely theoretical in nature to those directly applicable in practice, is increasing rapidly. We have been given the task from the University Administration and by our sponsoring organizations within DoD, and from various sectors within High-Technology Advanced Radar Industry to set up a "UNIVERSITY CENTER OF EXCELLENCE IN RADAR POLARIMETRY" together with a "CONSULTANT FIRM" (Polarimetrics Inc.).

The acquisition of an Advanced Polarimetric Radar Facility will further advance our future endeavors and the quality of our research. It will provide patentable innovation for all concerned.

II.5.3 Sharing of Facility and Production of an Expert Base in Radar Polarimetric Theory and Technology

With the gathered pioneering experts in radar polarimetry, we have been able to generate lively enthusiasm, loyalty, work persistence and high morale among our steadily increasing number of graduate research assistants with whom we are painstakingly reassessing the state-of-the-art in Radar Polarimetry. We have extended the monochromatic optimal polarization null theory to the quasi-coherent case; and similarly, we have generalized the monostatic, reciprocal case to the bistatic asymmetrical scattering matrix case which now allows us to analyze an increasingly larger spectrum of polarimetric radar research problems.

In developing a center in Advanced Polarimetric Radar Technology, every effort has already and will increasingly be made to have other research groups share the use of other advanced radar research equipment facilities. We have also attempted to unite research forces within laboratories of DoD, Industrial Institutions and Universities, and National/NATO Polarimetric Radar Research Laboratories for the design and development of National/NATO experimental facilities.

Therefore, the acquisition and funding of one or more Advanced Polarimetric Radar Imaging Systems is justified as long as these facilities will not be placed in static equilibrium, but it will be designed to be mobile, such that those can be mated with other advanced radar systems in symbiotic synchronization for the purpose of assisting all of us as one united research group.

II.5.4 Regional, National and NATO-Defense Benefits

The advancement of radar polarimetry occurs parallel with the advancement of high-technology microprocessor electronics which is also reflected by the great interest shown in our proposal effort by many High-Technology Radar Manufacturers, being leaders in advanced imaging radar systems. The enthusiasm with which ERIM, Boeing, Sperry, Scientific Atlanta, Honeywell, Bendix, etc. negotiated with us in designing and manufacturing a new polarimetric radar system may serve as a proof.

The recent "Falkland Island" adventures have clearly proven that we require an entirely new approach to modern smart seekers and/or fully automated robotics radar technology. The vastly exaggerated view of Eastern Technology to be unsophisticated must by now be a nightmare to all of us. However, we may still have a lead over the Eastern Colossus that wishes to attack us -- by integrating our high technology potentials and by mating advanced high resolution polarimetric radar robotics theories with advanced microprocessor ICS-chip technology.

Nationally, and on NATO interactive level, we do require interinstitutional interaction, because it will be impossible to concentrate a very large body of university professors, being research experts in a rather confined field at one university, e.g. the ElectroScience Laboratory of the Ohio State University; the Radiation Lab of the 1960's at the University of Michigan, etc. We, at EMID-CL-EECS-UIC have recently made every effort to set up such an interinstitutional, governmental-industrial-university intercorrelating research endeavor, engaging all national experts in our efforts of advancing radar polarimetry and extending our engagement to foremost experts of NATO member countries in good standing.

Yes, Last, but not least, we do carry and foster the bonds with our loyal NATO-partners, many of which are much closer to the forefront of interaction; therefore, the development of Advanced Polarimetric Broadband Down/Cross Range Imaging Radar facilities may renew the long overdue active involvement of expert scientists and DoD research labs of all NATO-member countries in good, loyal standing.

Considering the active role that our Communications Laboratory currently executes in NATO-research endeavors, which explicitly includes the advancement of polarimetric imaging radar technology, our request for Advanced Polarimetric Radar Systems is highly justified. Here, we must stress that the research expertise developed within our collaborating NATO-laboratories at RSRE/ASWE, DFVLR, NTNF, SHAPE-TC and FHP/FGAN represent major corner stone in the further advancement of high resolution polarimetric radar imaging. Therefore, every possible step must be made to support this important NATO interactive project.

II.5.5 Development of a New High-Technology R&D Base in Advanced Polarimetric Radar Imaging Robotics

Unless the serious state of affairs in current radar technology is comprehended immediately, we will experience a very disastrous wipe-out of radar industries similar to that which is currently occurring in the automobile industry. The mating of advanced Radar Polarimetry with High-Tech Micro-processor Technology has opened up an entirely new field of "NATIONAL BASE TECHNOLOGY". Not so much our European NATO-collaborators, but much more the Far Easterners (Japan/Korea/China) who need to manufacture new R&D armaments are a potential threat. Advanced Broadband Polarimetric Radar Imaging Robotics is a very new field; it is laughed at by the conservative radar industry, but it can easily be developed by small "Polarimetric Radar Computer Apples", i.e., DoD had better watch out for a polarimetric renaissance in Advanced Radar Technology.

CHAPTER III

III. ABSTRACTS OF M.Sc./Ph.D. THESES AND SHORT COURSE OUTLINES

Abstracts of M.Sc./Ph.D. theses and short course outlines are provided, including names of authors, date of approval and UIC-EECS-CL-EMID Report Numbers. These theses may be purchased as UIC-EECS-CL Reports.

- III.1 M.Sc. Theses Report Numbers, Names of Authors and Abstracts.
- III.2 Ph.D. Theses Report Numbers, Names of Authors and Abstracts.
- III.3 Short Course Outlines

III.1 M.Sc. Theses UIC-EECS-CL-EMID Reports

Rept No.	Author/Date of Approval/Title
80-1-16	Chuk-Min Ho (January 16, 1980), The Extension of Physical Optics Far Field Inverse Scattering Using Radon Transform Theories and Polarization Utilization.
80-10-30	Panagiota Mastoris (October 30, 1980), Transformation Invariances of the Polarization and Radar Scattering Matrices.
80-11-13	James B. Cole (Nov. 13, 1980), Design of an Experiment to Search for Power Line Harmonics Radiation Effects on the Magnetosphere.
81-05-21	Chung-Yee Chan (May 21, 1981), Studies on the Power Scattering Matrix of Radar Targets.
82-05-21	Bing-Yuen Foo (May 21, 1982), A High Frequency Inverse Scattering Model to Recover the Specular Point Curvature from Polarimetric Scattering Data.
82-06-18	Sadique M. Mullei (June 18, 1982), The Realization of Information from the Scattered Electromagnetic Wave Using the Polarization Parameters and the Poincare Sphere. (Project Report)
83-04-15	Marat Davidovitz (April 15, 1983), Analysis of Certain Characteristic Properties of the Bistatic, Asymmetric Scattering Matrix.
83-06-13	Sasan S. Saatchi (June 13, 1983), Estimation of Radar Target Signatures Using Scattering Matrix Data.
83-07-26	Jerald D. Nespor (July 26, 1983), Theory and Design of a Dual-Polarization Radar for Meteorological Studies.
84-01-06	Chau-Wing Yang (January 6, 1984), Extension of Scalar to Vector and Tensor Diffraction Tomography.
84-01-01	Benjamin Beker (In completion), Radiation from Thick Parabolic Reflectors.
84-01-02	Xiao-Qing Huang (In completion), Lambert, Mollweide and Aitoff Projections of the Polarization Sphere and its Application to Radar Polarimetry.
84-01-03	Robert B. Lempkowski (In completion), A Modular Testbed Design of a High Resolution Polarization Radar for Target in Clutter Detection and Description.
84-01-04	Anthony C. Manson (In completion), A Classification Analysis of High Resolution Polarimetric Target Downrange Signatures Based on Kennaugh's Polarimetric Target Characteristic Operator Theory.
84-01-05	"High Resolution RCS Studies of Simple Targets"

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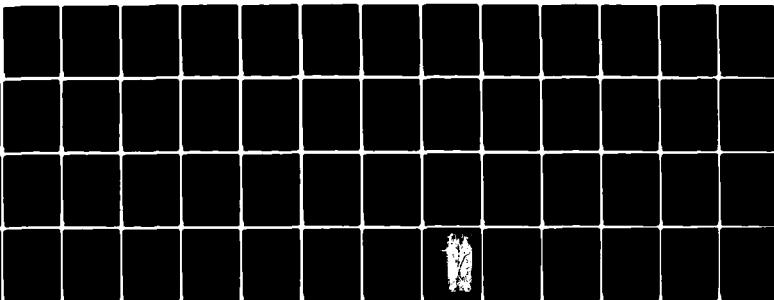
POLARIZATION UTILIZATION IN RADAR TARGET
RECONSTRUCTION: C-WIDE (MULTI-FR.) ILLINOIS UNIV AT
CHICAGO CIRCLE ELECTROMAGNETIC IMAGING DIV
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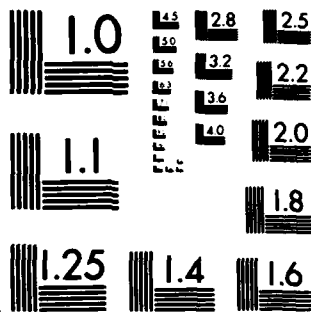
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Abstracts of M.Sc. Theses
January 16, 1980
Chuk-Min Ho: M.Sc

THE EXTENSION OF PHYSICAL OPTICS FAR FIELD INVERSE SCATTERING
USING RADON TRANSFORM THEORIES AND POLARIZATION-UTILIZATION

In the inverse scattering problem for perfectly conducting objects, the reconstruction of the shape and size of a convex body from its cross-sectional areas has been formulated as a Radon problem of image reconstruction from projections. It is shown here that the Physical Optics inverse scattering time-domain and frequency-domain identities form a Radon-Fourier transform pair, and the problem of target reconstruction from incomplete data is common to both.

The mathematical aspects of reconstruction from projections is examined using concepts of Radon's theory, and the sparse data problem is analyzed. The limited aperture is solved via the Radon transform approach utilizing properties of Ludwig's theorem on supports.

In order to obtain more accurate cross-sectional areas for reconstruction, polarization utilization is investigated to correct the polarization-independent deficiency of the Physical Optics approximation. The technique is applied to the case of a sphere-capped cylinder and the results show substantial improvements above previous scalar approaches. It is concluded upon decisive computational/-experimental results that the three practical problems often encountered in numerical reconstruction, namely: (i) frequency band-width limitation, (ii) sparse projection direction, (iii) inaccurate (or inconsistent) projection data, all have an interrelated effect in the reconstruction process, such that improving one will decrease the detrimental effect of the other.

October 30, 1980
Panagiota Mastoris: M.Sc

TRANSFORMATION INVARIANCES OF THE POLARIZATION
AND RADAR SCATTERING MATRICES

The importance of utilization of the concept of polarization in radar target related phenomena has become very apparent in the recent years. But the most significant results obtained thus far, are available in terms of information contained within the components of the Radar Cross Section Scattering Matrix, whereas the use of the Mueller Matrix has been overlooked.

As explained in this thesis, there is convincing evidence that the Mueller matrix elements behave in a manner characteristic of the material properties of the specific type of clutter they represent. Though the interpretation of this behavior needs further investigation, one can safely assume that the information provided by the matrix [M] can be very useful in establishing target and particularly clutter characteristics, especially for the incoherent scatter case. Moreover, due to the "additivity" property of the Stokes parameters of independent waves, the independent incoherency properties of clutter are exhibited explicitly in the matrix [M] while they are only implicitly inherent in the RCS matrix. Because of this it has been recognized that the covariance

matrix discriminant technique for the incoherent clutter case will bring superior results when applied to the [M] matrix, than when applied to the scattering matrix [S].

In addition to the above, it has been found that most of the statistical clutter data available are given in terms of the components of [M]. Hence, in order to interpret scatter characteristics polarization properties in terms of its associated co/cross-polarization null statistics on the Poincare sphere, it would be highly practical to express the coordinates of optimal polarizations in terms of the components of the Mueller matrix [M].

In view of the above, we have investigated here the Mueller matrix. First we tackle the problem of reconstructing the scattering matrix from the Mueller matrix. This problem is of practical importance because it is simpler to measure the Mueller elements and yet they contain the same amount of information as the scattering matrix. Moreover, one needs to measure only amplitudes (power) and no phase measurements are needed. A solution to this problem is given in Chapter IV where the elements of matrix [S] are reconstructed with relative phases. Second, the two pairs of optimal polarizations are expressed in terms of the Mueller matrix components M_{ij} .

November 13, 1980
James Bradford Cole: M.Sc

DESIGN OF AN EXPERIMENT TO SEARCH FOR POWER LINE HARMONICS RADIATION EFFECTS ON THE MAGNETOSPHERE

Very low frequency (VLF) radiation from electric power lines is strongly suspected to initiate and control magnetospheric chorus over regions of high electrical consumption and transmission. Power line VLF can be amplified up to 1000-fold in the magnetospheric plasma in an as yet incompletely understood wave-particle interaction. These amplified electromagnetic waves interact with charged particles in orbit about the geomagnetic field lines to produce particle precipitation fluxes of more than 10^6 the input wave power onto the ionosphere. Precipitated particles increase the electrical conductivity of the D and E regions which increases the absorption of electromagnetic waves that pass through or reflect from these regions. The possibility that the electrical properties of the upper atmosphere might be perturbed sufficiently to influence the atmospheric electrical circuit cannot be excluded. Power line VLF is currently believed to be at least partly responsible for the $2 < L < 3$ electron slot between the inner and outer magnetospheric radiation belts.

To test and develop current theory regarding the role of power line VLF in the magnetosphere quantitative information is required on how much power line VLF reaches the magnetosphere, and on how once there it interacts with the plasma. One major experimental difficulty is to discriminate between natural effects and those due to power line VLF. The purpose of this thesis research is to propose a set of experiments that can at least reduce the number of possible theories regarding the role of man-made VLF in magnetospheric processes.

May 21, 1981
Chung-Yee Chan: M.Sc

STUDIES ON THE POWER SCATTERING MATRIX OF RADAR TARGETS

Various representations of the polarization of an electromagnetic plane wave are presented, with special reference to antenna polarization.

The formulation, characteristics and measurement of the monostatic coherent Sinclair's scattering matrix, Graves' power scattering matrix, symmetric Mueller matrix and the incoherent symmetric average Mueller matrix of radar targets are also discussed. In particular, it is shown that the power scattering matrix can be decomposed into two supplementary matrices which are then used to reconstruct the scattering matrix with relative phase and the symmetric Mueller matrix.

A method of determining the optimum polarization for maximum total backscattered power ratio between target and clutter is presented. This method involves straight-forward differentiation of the backscattered power ratio and the solution is expressed in terms of elements of power scattering matrices. The use of Kennaugh's co-polarization null (COPOL null) concept of optimum polarization in target versus clutter discrimination studies is also discussed.

May 21, 1982
Bing-Yuen Foo: M.Sc

A HIGH FREQUENCY INVERSE SCATTERING MODEL TO RECOVER THE SPECULAR POINT CURVATURE FROM POLARIMETRIC SCATTERING DATA

Based on the time-domain first order correction to the physical optics current approximation, a relationship between the phase factors of the polarimetric scattering matrix elements and the principal curvatures at the specular point of a scatterer is established.

The above phase-curvature relationship is tested by applying it to theoretical as well as experimental backscattering data obtained for a prolate spheroidal scatterer. The results of these tests not only determine the acceptability of the phase-curvature relationship, they also point out the range of kb values over which the first order correction to the physical optics currents is valid, and which serves as a compromise range between the high frequency condition required by the curvature recovery model and the drawback to lower frequencies required to prevent critical magnification of measurement errors.

Another curvature recovery equation is derived by transforming the linear polarization basis to the circular polarization basis. The curvature recovery model is proven to satisfy the image reconstruction identities of invariant transformation. A scattering ratio is defined and its behavior is investigated at high frequencies. Its plot on the complex plane provides a simple way to help judge the accuracy of polarimetric scattering measurements, regardless of whether a linear or a circular polarization basis is used.

June 18, 1982

Sadique M. Mullei: M.Sc (Note: Only a Project Report!)

THE REALIZATION OF INFORMATION FROM THE SCATTERED
ELECTROMAGNETIC WAVE USING THE POLARIZATION PARAMETERS AND
THE POINCARÉ SPHERE

Radar target identification can be realized by the use of polarization parameters of a scattered electromagnetic field. This approach is a direct response of the target thus providing a more realistic representation of the actual object. However, total recording of the information in the scattering matrix [S] by accounting for all five components is essential for complete target information.

The natural complexity of the topic is a fact well appreciated by the author, but its importance and the love for exploration of natural phenomenon have had priority in his attempt to tackle the subject. Many publications are not new inventions but expansions on the well-known theories and this one is no exception. Therefore, the theories compiled in this thesis are extracted from various publications as is provided in the references and have not been developed by the author as such. Nevertheless, they intuitively impress the author as bearing weight in applied techniques in the scattering and extraction of the information contained in the propagated electromagnetic wave. The author hopes that if these theories are properly understood and extrapolated in radar target identification it will result in significant improvement.

Due to lack of facilities the author did not test these intuitions but he is committed to expounding on each one of them in the near future whenever the opportunity exists.

April 15, 1983

Marat Davidovitz: M.Sc

ANALYSIS OF CERTAIN CHARACTERISTIC PROPERTIES OF THE
BISTATIC, ASYMMETRIC SCATTERING MATRIX

The optimal polarization properties of the radar scattering matrix [S(A,B)] are investigated for the general bistatic asymmetrical case. The degenerate cases of the non-reciprocal monostatic scattering matrix and the symmetrical monostatic scattering matrix are used to demonstrate the existing differences which affect monostatic vs. bistatic, as well as polarimetric target null signature interpretation.

Reduction of bistatic scattering matrix measurements for inversely symmetric radar targets is also considered. The inversion symmetry relations between the elements of the matrix are introduced, based upon simple geometrical arguments. These relations are subsequently combined with the principle of electromagnetic reciprocity. The results are used to determine the least number of measurements needed to completely specify bistatic scattering from objects with inversion symmetry. If the target is also a body of revolution, even a greater reduction in the number of bistatic measurements required to completely characterize the object is possible. This is proven utilizing the principle of polarization reversal reflection symmetry.

Numerical verification of the symmetry relations is performed for prolate and oblate spheroidal scatterers for the bistatic measurement setup.

June 13, 1983
Sasan S. Saatchi: M.Sc

ESTIMATION OF RADAR TARGET SIGNATURES
USING SCATTERING MATRIX DATA

The utilization of polarization in radar target scattering provides a number of scatterer descriptive operators which are used to determine a classification method based on target polarization dependent properties. It also provides insight into polarimetric radar antenna measurement procedures.

To show the validity of the above argument, a set of formulas for various representations of polarization characteristics of radar targets are derived and the use of a transformation method to verify the effectiveness of the formulas is suggested.

In addition, a method to introduce the error sources in radar polarization measurements and to associate the errors in the polarization descriptive operators is provided.

An established computer program for field solutions of bodies of revolution is used to illustrate the polarization dependence of the backscattered measurement of ellipsoidal targets. Furthermore, a phase relation is introduced between the scattering matrix elements of two independent targets in order to demonstrate the polarization properties of dumbbell model targets.

July 26, 1983
Jerald D. Nespor: M.Sc

THEORY AND DESIGN OF A DUAL-POLARIZATION RADAR
FOR METEOROLOGICAL STUDIES

Current meteorological information concerning characteristics of precipitation shape and orientation is obtained from circular and linear dual polarization measurables usually derived from auto-correlations and cross-correlations of the main and orthogonal channels.

An alternative formulation is presented which deduces meteorological information from time series measurements of the relative backscattering matrix. This alternative formulation, namely the optimal polarization concept, is developed from the coherency matrix for both completely and partially polarized signals. The formulation is in terms of the parameter used to calculate the elliptical depolarization ratio, but the general formulation can also be used for radar that have circular, as well as elliptical polarization capabilities. The elements from a single measurement of the relative backscattering matrix can be used to calculate optimal polarizations, i.e., co and cross pol nulls mapped on the polarization sphere of Poincare, and the polarization chart. The sensitivity of the time series clustering of the co-pol nulls to variations in axis ratios of rain is investigated.

A backscattering model for a volume of oblate spheroidal raindrops is then developed that takes into account the beam elevation angle and the raindrop canting angle and can be seen to be applicable to systems utilizing linear, circular, or elliptical polarizations.

The DFVLR agile dual polarization diverse radar design concept is then discussed and shown to be feasible for making the measurements necessary to further investigate the theory presented herein.

January 06, 1984
Chau-Wing Yang: M.Sc

EXTENSION OF SCALAR TO VECTOR AND TENSOR DIFFRACTON TOMOGRAPHY

The scalar theories of acoustic diffraction tomography have been developed for both backprojection and the back-propagation methods. Here, we extend it to the electromagnetic case taking the vector nature into account.

First, the general formulation of the vector diffraction problem is considered in detail for strongly, as well as weakly discontinuous, inhomogeneous media. Whereas, for strongly inhomogeneous media, it is presently not possible to formulate a solution for the weakly discontinuous, inhomogeneous case for which the Born and Rytov approximations apply, various methods of solutions are proposed. Applying Jones' transmission matrix calculus, the vector forward scattering properties of the discontinuity within each slice transverse to propagation direction is described by an effective transmission sub-matrix. The individual sub-matrices are then properly post-multiplied for each additional slice resulting in the total transmission matrix. To obtain a first order solution to the problem, the back-propagation and back-diffractive algorithms derived for the scalar case are then applied independently to the four components of the transmission matrix, where here a linear H,V polarization basis is introduced. First order corrections to this approach are suggested.

As a practical example, the modeling of the Faraday effect was considered to reconstruct the rotation angle and by utilizing standard relations of plasma dynamics it is shown how the inhomogeneous electron density profile and the index of refraction profile of an inhomogeneous media excited by an externally applied magnetic field parallel to wave propagation may be reconstructed.

1984 (In completion)
Xiao-Qing Huang: M.Sc

LAMBERT, MOLLWEIDE AND AITOFF PROJECTIONS OF THE POLARIZATION SPHERE AND ITS APPLICATION TO RADAR POLARIMETRY

In the application of basic scattering matrix theories such as Kennaugh's target characteristic operator formulation to radar polarimetry, optimal polarization states need to be displayed on the Poincare polarization sphere. Although such a three-dimensional presentation of a radar target's characteristic operator (polarization fork) is most illustrative, in practice two-dimensional projections are usually more desirable; and here we will apply modern and advanced methods of cartographic projection theory for the purpose of determining which planar projection can be used efficiently next to the standard polar map projection.

Specifically, we will discuss techniques of presenting power and voltage relationships on the Poincare polarization sphere on two-dimensional planar maps using various projection algorithms. With the assumption of only being concerned with the specific location of a polarization state on the polarization sphere rather than its intensity, we normalize the Poincare sphere to be a unit sphere so that a reduction from the three-dimensional projection can be facilitated. Various known geographical mapping techniques are applicable in this case which differ in such properties as the shape, the size, the area distortion of specific regions on the sphere. In general, those techniques can be set in order of four categories, namely: Azimuthal, Cylindrical, Conic, and Elliptical. The characteristics of these techniques are discussed, associated computer graphical software was developed, as well as applied documentation and implementation analyses for many polarimetric radar applications are introduced. Specifically, the standard polar projection, various Lambert projections, the elliptical Aitoff and Mollweide approaches are considered in detail.

Finally, using experimental and computer model generated data, these various projection techniques are applied to practical situations, and their relative merits are being discussed and compared.

1984 (In completion)
Robert B. Lempkowski

A MODULAR TESTBED DESIGN OF A HIGH RESOLUTION POLARIZATION RADAR FOR TARGET IN CLUTTER DETECTION AND DESCRIPTION

Recent developments in radar polarimetry have generated diverse requirements for system design. Special purpose radars have proven key aspects of the expanding use of dual orthogonal theoretical work. A system which can accommodate varieties of polarization diverse operating modes is required to further expand this capability by providing insights into target and/or clutter depolarization properties. Improvements with regard to real-time viewing of processed data is imperative for system and operator interaction to optimize algorithms of the various operating modes.

This system proposal entails the use of a variable ellipsometric polarization transmitter and a receiver which displays return polarization operating from 2-18 GHz. Transmission can be routed into the receiver for system calibration error correction, and resulting real time depolarization display utilizing digital controlled switch, phase and amplitude networks located in both the transmitter and receiver. The display format is the Poincare sphere itself, and the vector information of co-pol nulls is available for immediate further processing when formed via transmission of variable polarizations. Separate orthogonal channels are available in the receiver to monitor x-pol information as well as prove correctness of co-pol ratio returns of the display.

In addition to functioning as a polarimetric radar, additional modes to be used separately for investigation are:

1. Individual orthogonal doppler channels.
2. Amplitude and frequency modulation for ramp, chirp and other compressive modes.
3. Polarization modulation ability (digital) for communication or serrodyne.

Since the receiver has the orthogonal channels available, the possibility exists for growth into the following areas:

1. Upconvert/downconvert to higher frequency capability with an odd common IF.
2. Employ use of other special-purpose hardware such as logic-product null suppression techniques.
3. Combinations of techniques, chirp filter hardware, etc.

1984 (In completion)
Anthony C. Manson

A CLASSIFICATION ANALYSIS OF HIGH RESOLUTION POLARIMETRIC
TARGET DOWNRANGE SIGNATURES BASED ON KENNAUGH'S POLARI-
METRIC TARGET CHARACTERISTIC OPERATOR THEORY

Basic polarimetric backscattering characteristics of simple to increasingly more complex shaped missile-type targets are analyzed and interpreted by adhering strictly to Kennaugh's target characteristic operator concept and Huynen's target Mueller-matrix decomposition theories.

Scatterer model data are computer-generated on the DEC-VAX 11/750 Research Computer Processing System at the Communications Laboratory and compared with measurement data for missile-type composite targets collected on the Teledyne-Micronetics range for the S-band (2.4 to 4 GHz in steps of 25 MHz) and X-band (9 to 10.6 GHz) for vertical (V) and horizontal (H) antenna polarization state basis as described in Morgan and Weisbrod (1982).

Major emphasis is placed on extracting basic polarimetric scattering/diffraction centers of single isolated composite targets of missile shape as functions of aspect and incremental down range resolution. The obtained results are reinterpreted with the objective of assessing the potential of utilizing complete polarimetric target downrange signatures as input function for target characteristic classifiers.

1984 (In completion)
Benjamin Beker

RADIATION FROM THICK PARABOLIC REFLECTORS

The two-dimensional problem of radiation from a parabolic cylindrical metal reflector fed by a parallel-plate waveguide located in the focal region of the reflector is considered. The finite thickness of the reflector is taken into account, and the two edges are modeled by a thick half-plane which is either abruptly truncated or rounded smoothly via a semicircular profile.

The integral equation for the surface current density on the reflector is solved numerically, and the far-field pattern is obtained. The results are compared with those available for a reflector of infinitesimal thickness. The effects of thickness and of edge termination on both the surface current distribution and the radiated field pattern are discussed.

In the far field, the numerical results are compared with the analytical predictions based on a combination of the geometrical theory of diffraction (including slope diffraction coefficients) and of Fock's theory. All results are given for both TE and TM polarizations. The extension to three dimensions (paraboloidal reflector) is also discussed.

1984 (In preparation)
Sheng-Ming Huang

EXTRACTION OF POLARIMETRIC TRANSIENT RAMP RESPONSE SIGNATURES FROM POLARIMETRIC TARGET DOWN RANGE-MAPS FOR THREE-DEMINSIONAL TARGET SHAPE RECONSTRUCTION.

In this computer-numerical/graphical analysis of the polarimetric target down range maps of missile-type targets as provided in

"Boerner, Manson, Huynen - Radar Target Classification Using Polarimetric Target Slant Range Signatures", Naval Air Systems Command, Final Report
#UIC-EMID-CL-82-06-15, June 15, 1983

the objective is to recover useful time-domain data which can be used for three-deminsional shape reconstruction based on Kennaugh's transient ramp response method, as well as, Kennaugh's polarimetric target characteristic operator description. First it is shown how the transient ramp response signatures can be recovered from the raw measurement data obtained with the frequency stepping procedure of the Teledyne-Micronetics high resolution S/X-band polarimetric radar system. Based on the analytical description of the imaging algorithm, the logical primitives are extracted and placed in a data-base and initially queried using the Datatrieve - Data-Base language utility. Procedures are then formulated under datatrieve capable of extracting a multitude of useful polarimetric signature combinations derived from Kennaugh's and Huynen's target phenomenological theories on the logical data base. This data base extracted from "polarimetric base theory" is crucial in generating complex queries that are meaningful in terms of physically observable target shape characteristics along target down range.

The development of computer graphical display procedures for target imaging and identification is perused using the Teledyne-Micronetics Data for model verification which are provided in

"Morgan and Weisbrod - RCS Matrix Studies of Simple Targets, Final Report, TDYMIC-R2-82 Teledyne Micronetics, March 1972"

and

"Morgan and Weisbrod - High Resolutions RCS Matrix Studies of Simple Targets, Rept. R14-82, Teledyne-Micronetics, June 1982"

III.2 Ph.D. Theses UIC-EECS-CL-EMID Reports

<u>Rept. No.</u>	<u>Author/Approval Date/Title</u>
84-02-01	Ali M. Khounsary (In final preparation), Polarimetric Radiative Transport Description of Propagation Through Ensembles of Discrete Scatterers in Inhomogeneous Media.
84-02-02	Vithal K.S. Mirmira (In completion), Polarimetric Dependence of Residues in the Radar Target Resonance Description.
85-02-01	Amit P. Agrawal (In final preparation), A Model-Free Polarimetric Clutter Description Derived from Kennaugh's Target Characteristic Operator Theory Formulated in Coherency Matrix Notation.
85-02-02	Bing-Yuen Foo (In final preparation), Application of the Vector Extension of Kennaugh's Transient Target Impulse Response Method to 3-Dimensional Target Imaging Using High Resolution Polarimetric Radar Measurement Data.

Abstracts of Ph.D. Theses
1984 (In Final Preparation)
Ali M. Khounsary (1984): Ph.D

POLARIMETRIC RADIATIVE TRANSPORT DESCRIPTION OF PROPAGATION THROUGH
ENSEMBLES OF DISCRETE SCATTERERS IN INHOMOGENEOUS MEDIA

The study of electromagnetic wave propagation in random media has attracted increasing attention in recent years, particularly in response to the advent of terrestrial and earth-space communication systems, and also as a result of its applications in such fields as radar detection and radar remote sensing.

An important feature of electromagnetic wave propagation in random media which has, until recently, received less attention is multiple scattering and the resulting incoherent field. Multiple scattering effects in many instances can be neglected while in others their inclusion may be imperative. For example, in the area of satellite communication, saturation of low and moderate frequency channels has resulted in utilization of higher operating frequencies at which multiple scattering due to the presence of hydrometeors along the propagation path gives rise to incoherent fields, depolarization and cross-polarization, i.e., the vector nature of the electromagnetic wave scatterer interaction can no longer be neglected at these wavelengths.

One approach to the problem of multiple scattering is provided by the radiative transport theory. This theory which is valid for media with low particle density is considered to be the closest to a general formulation of particulate scattering, for it imposes no direct restriction on size, shape, or properties of the scatterers. Furthermore, through the introduction of the Stokes parameters, the vector radiative transport theory can be used to include polarization information.

The radiative transfer equation which governs the variation of intensity in participating media, has not yet been solved in its general three dimensional form. However, several solution procedures for the case of plane parallel media are available. The adding-doubling method which is used in this study is one such procedure. It begins with a layer of differential optical depth of the medium for which the single scattering approximation is valid. By adding this layer to itself, whereby doubling the optical depth and repeating this process, the solution for finite plane parallel media is obtained. For inhomogeneous plane parallel media, finite homogeneous layers are constructed and then added.

The adding-doubling method in its scalar form has been used to obtain the radiative field in both homogeneous and inhomogeneous media. Using its vectorial form (to include polarization) transmission and reflection functions for a homogeneous plane-parallel medium containing spherical scatterers have also been obtained.

In the present study, we consider the case of inhomogeneous plane parallel media with a reflecting boundaries and develop via the adding doubling routine an efficient computer code for the solution of the vector radiative field. The accuracy of the solution is assessed and the possibility of extending the method to denser media of non-spherical scatterers, and to two and three dimensions is investigated.

1984 (In completion)
Vithal K.S. Mirmira: Ph.D

POLARIMETRIC DEPENDENCE OF RESIDUES IN THE
RADAR TARGET RESONANCE DESCRIPTION

The singularity expansion method (SEM) is used to study the characteristic properties (e.g. estimates on material properties and shapes) of the scatterer.

We review the various fields where SEM and its counterparts are used to study such diverse effects as defects in solids (acoustics), interaction of elementary particles (regge-pole theory) and radar target identification in electromagnetic scattering.

We conclude the review with an analysis of the polarization dependence on SEM: we specifically look at a plane-wave impinging on a thin wire, studying polarization sensitivity of the residues associated with the eigenresonances.

1985 (In Final Preparation)
Amit Prakash Agrawal: Ph.D

A MODEL-FREE POLARIMETRIC CLUTTER DESCRIPTION DERIVED FROM KENNAUGH'S
TARGET CHARACTERISTIC OPERATOR THEORY FORMULATED IN COHERENCY MATRIX NOTATION

It is shown how Kennaugh's target characteristic operator theory for the single scatterer case expressed in terms of the 2×2 radar scattering matrix can be generalized for polarimetric description of clutter, i.e., distributed multiple scatterer ensemble, in terms of the mean co-polarization, mean cross-polarization nulls and their spreads about the mean. This novel theory is then applied to various specific types of hydrometeoric sea, vegetation and terrain clutter demonstrating how the average shape, orientation and spatial distribution of scatterer ensembles can be expressed in terms of the mean optimal polarization nulls and their spreads, respectively. The theories derived for the static case are further extended to the description of motional clutter in terms of dynamic polarization fork motion on the polarization sphere as functions of aspect, frequency and scatterer motions allowing a physical interpretation of the micro-time scale motion group of scatterers within a scatterer ensemble (clutter). The theories developed are verified by analyzing various experimental data. The new concept of designing multi-notch dynamic multi-notch polarimetric radar clutter suppression filters is discussed based on the application of the model-free clutter descriptive theory developed in this thesis.

1985 (In Final Preparation)
Bing-Yuen Foo: Ph.D

APPLICATION OF THE VECTOR EXTENSION OF KENNAUGH'S TRANSIENT TARGET IMPULSE
RESPONSE METHOD TO 3-DIMENSIONAL TARGET IMAGING USING HIGH RESOLUTION
POLARIMETRIC RADAR MEASUREMENT DATA

In continuation of the M.Sc. thesis (B-Y. Foo), research on extending Kennaugh's transient ramp response method to the polarization vector case utilizing Bennett's first order correction to the Physical Optics current approximation, the second and higher order corrections resulting from the vector diffraction integral will be considered. Using this result, major emphasis will be placed on polarimetric target imaging incorporating:

- (i) for pure target down-range imaging Kennaugh's target characteristic operator and Huynen's Mueller matrix decomposition theories,
- (ii) for multi-aspect data (monostatic) the Radon transform approach explored in the M.Sc. thesis of C-M. Ho and M.Sc./Ph.D. theses of C-M. Ho and Y. Das extending J.D. Young's approach.

The analytical methods will be verified utilizing broadband complete scattering matrix data generated on the indoor compact range of ESL/OSU, Columbus, OH., and at Teledyne Micronetics, San Diego, CA.

III.3

SHORT COURSE OUTLINES

III.3.1 ONE-DAY RESEARCH SHORT COURSE

on
**BASIC & ADVANCED RADAR POLARIMETRY AND ITS APPLICATIONS TO
NON-COOPERATIVE TARGET IN CLUTTER DETECTION, DISCRIMINATION,
CLASSIFICATION, IMAGING AND IDENTIFICATION**

by
Wolfgang-M. Boerner

8:30 - 9:00 Opening Remarks & Introduction of Participants

PART I: BASIC THEORY

9:00 - 10:00 Basic Polarimetric Radar Target Descriptors
(Polarization Sphere, Scattering Matrices)

10:00 - 11:00 Kennaugh's Target Polarization Null Theory

11:00 - 12:00 Huynen's Target Characteristic Description of
the N-Target Decomposition Theory

PART II: APPLICATIONS

1:30 - 2:30 Polarimetric Requirements for Radar Target in
Clutter Detection, Discrimination, Classification,
Imaging & Identification

2:30 - 3:30 Polarimetric Target & Clutter Mapping Methods

3:30 - 4:30 Open Discussion

4:30 - 5:00 Isolation of Problems of Mutual Interest:
Initiation of Consulting & Contract Negotiations

5:00 **Adjournment**

III.3.2 TWO DAY SHORT RESEARCH COURSE OUTLINE

on
BASIC & ADVANCED RADAR POLARIMETRY AND ITS APPLICATIONS TO NON-COOPERATIVE TARGET
IN CLUTTER DETECTION, DISCRIMINATION, CLASSIFICATION, IMAGING AND IDENTIFICATION
by
Wolfgang-M. Boerner

DAY 1

8:30 - 9:00 Opening Remarks and Introduction of Participants

PART A: BASIC THEORY
9:00 - 10:00 Radar Target Signature Analysis: an electromagnetic vector
inverse problem

10:00 - 11:00 Radar Target Polarization Descriptors

11:00 - 12:00 Radar Target Scattering Matrices and Presentations

Lunch Break

PART B: RADAR TARGET PHENOMENOLOGY
1:30 - 2:00 Basic Radar Target Descriptors

2:30 - 3:30 N-Target Decomposition Theory: Clutter Handling

3:30 - 4:30 Polarimetric Hardware Design

4:30 - 4:45 Adjournment

DAY 2

8:30 - 9:30 Introduction of Participants

PART C: APPLICATIONS
9:30 - 10:30 Polarimetric Target Down-range Mapping: Classification

10:30 - 11:30 Polarimetric Target Imaging

11:30 - 12:30 Panel Discussion on Needs for Advancement of Radar
Polarimetry for Applications in Multi-Sensor Seeker Radar
Modes of Application
W-M. Boerner, R. Suresh, and Participants

Lunch Break

PART D: OPEN DISCUSSION
1:30 - 2:30 Isolation of Problems of Mutual Interest (Research Staff)

2:30 - 3:30 Initiation of Consulting and Subcontract Negotiations

3:30 Adjournment

III.3.3 EXTENDED TWO-DAY RESEARCH SHORT COURSE

on
BASIC & ADVANCED RADAR POLARIMETRY AND ITS APPLICATIONS TO NON-COOPERATIVE TARGET
IN CLUTTER DETECTION, DISCRIMINATION, CLASSIFICATION, IMAGING AND IDENTIFICATION

by
Wolfgang-M. Boerner, J. Richard Huynen and Anthony C. Manson

DAY 1

8:30 - 9:00	Opening Remarks and Introduction of Participants
	PART A: BASIC THEORY
9:00 - 10:00	Radar Target Signature Analysis: an electromagnetic vector inverse problem W-M. Boerner
10:00 - 11:00	Radar Target Polarization Descriptors W-M. Boerner
11:00 - 12:00	Radar Target Scatteromg Matrics and Presentations W-M. Boerner & A.C. Manson
	Lunch Break
	PART B: RADAR TARGET PHENOMENOLOGY
1:30 - 2:00	Basic Radar Target Descriptors J.R. Huynen
2:30 - 3:30	N-Target Decomposition Theory J.R. Huynen and A.C. Manson
3:30 - 4:30	N-Target Residue Analysis: Clutter Handling J.R. Huynen
4:30 - 4:45	Adjournment

DAY 2

8:30 - 9:00 Introduction of Participants

PART C: APPLICATIONS

9:00 - 9:30 Polarimetric Requirements for Radar Target in Clutter
Discrimination, Classification, Imaging and Identification
W-M. Boerner

9:30 - 10:30 Polarimetric Target versus Clutter Discrimination: Poelman's
non-linear multimatch polarization vector transformation
W-M. Boerner

10:30 - 11:30 Polarimetric Target Down-Range Mapping: Classification
A.C. Manson & J.R. Huynen

11:30 - 12:30 Polarimetric Target Imaging
W-M. Boerner

Lunch Break

PART D: OPEN DISCUSSION

1:30 - 2:30 Panel Discussion on "Needs for Advancement of Radar
Polarimetry"
W-M. Boerner, J.R. Huynen, A.C. Manson and Research Staff

2:30 - 3:30 Isolation of Problems of Mutual Interest (Research Staff)

3:30 - 4:30 Initiation of Consulting and sub-contract negotiations

4:30 Adjournment

CHAPTER IV

IV. SPECIAL CITATIONS/EDITORSHIPS/PUBLICATIONS/SHORT COURSE PRESENTATIONS

In the following, details for the above are presented in chronological order. Please note that citation documents, reprints, etc. are not attached, but will be furnished upon request.

- IV.1 Citations Awarded
- IV.2 Editorships
- IV.3 Publications
- IV.4 Conference/Workshop Presentations
- IV.5 Short-Courses Presented

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IV.1 Citations Awarded

Alexander von Humboldt Society for the Advancement of Science (FR Germany)
Fellow Award, "For Advancement of Electromagnetic Imaging Techniques," 1980.

President, Polarimetrics, Inc., Northbrook, IL. (Consultants in Applied
Electromagnetics, Remote Sensing and Polarimetric Radar Theory &
Technology), June 23, 1981.

NATO-IMOR Senior Scientist Fellow, "For Advancement of High Resolution Radar
Polarimetry," April 1982 (with SHAPE-TC).

IEEE Fellow Grade, "For Advancement in Inverse Methods in Sensing Systems
and in High Resolution Broad Band Doppler Radar Polarimetry," November 21,
1983.

IV.2 Editorships

IEEE, Antennas & Propagation Society, Transactions, Associate Editor
(Inverse Methods and Imaging), since January 1980.

IEEE, Transactions Antenna & Propagation, Vol. 29(2), 1981 Special Issue,
Inverse Methods in Electromagnetics, Guest Editor, 1980-1981, (417 pages).

NATO Advanced Research Workshop on "Inverse Methods in Electromagnetic
Imaging", September 18-24, 1983, Proceedings, Chief Editor, 1982-1984, (1600
pages.).

Royal Society of Physics (UK), Journal of Physics, Section E, (new: First
International) Inversion Methods in the Physical Sciences, Associate Editor
(electromagnetic/vector), since December 1983.

IV.3 Publications:

(B=Book, M=Monograph, E=Edited Paper, P=Refereed Paper, C=Refereed
Conference Proceedings, W=Workshop Contribution, I=Invited Paper, R=Report,
S=Symposium/Conference Paper)

1980

Boerner, W-M., Polarization Utilization in Electromagnetic Inverse
Scattering, Chapter 7 in "Inverse Scattering Problems in Optics", Vol. II
(ed. H.P. Baltes), Topics in Current Physics, Vol. 20, Springer Verlag,
Sept. 1980, pp. 237-305. (Also see: W-M. Boerner, Polarization Utilization
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Scattering, A STATE-OF-THE-ART Review, Comm. Lab. Report #78-3, October
1978). (M)

Boerner, W-M., Importance of Radon's Projection Theory in Electromagnetic
Imaging, Kleinheubacher Tagung (URSI-Comm. B., FR West Germany), Oct. 8-12,
1979, published in Kleinheubacher Tagungsberichte, Vol. 23, 1980, pp.
383-393. (W)

Boerner, W-M., Development of Physical Optics Inverse Scattering Theory, 1979 Conference on Math. Methods & Applications of Scattering Theory, Catholic University, Washington, D.C., U.S.A., May 21-25; ed. by J.A. DeSanto, A.W. Saenz, W.W. Zachari, Lecture Notes in Physics (Springer Verlag, New York, 1980), pp. 301-307. (C)

Boerner, W-M., Polarization Microwave Holography: An Extension of Scalar to Vector Holography (INVITED), 1980 International Optics Computing Conference, SPIE's Techn. Symposium East, Washington, D.C., April 9, 1980, Sess. 38, paper No. 231-23 pp. 188-198, 1980. (I/C)

Boerner, W-M., Inverse Scattering in Electromagnetic Medical Imaging, (INVITED paper No. 2, 15 pages, Chapter 2), Electromagnetic Dosimetric Imagery Symposium, 27 May 1980, Washington, D.C. Proceedings by Mack Printing Co., Easton, PA. (M)

Boerner, W-M., Ho, C-M., Extension of Physical Optics Inverse Scattering Using Polarization Information, Special Poster Session on Inverse Scattering III (Joint URSI Comm. B, IEEE-APS), North American Radio Science Meeting and IEEE/AP-S International Symposium, Universite Laval, Quebec, Canada, June 2-6, 1980. (S)

Boerner, W-M., Goddard, W.R., Cole, J., Thio, C, Measurement and Analysis of Controlled Powerline VLF Radiation from the HV-DC Line Radison-Dorsey, Manitoba, Special Session on "Electromagnetic Induction from Overhead Conductors (INVITED) URSI-B, N. American Radio Science Meeting and IEEE/AP-S International Symposium, Universite Laval, Quebec, Canada, June 2-6, 1980. (S)

Boerner, W-M., Use of Polarization Information in Electromagnetic Inverse Scattering, Inverse Scattering Session III, Paper No. 1, 1980 International URSI-Comm. B., Wave Propagation Symposium, Munich, FR Germany, August 26-29, 1980. (S)

Boerner, W-M., Impacts of Solar and Auroral Storms on Power Line Systems, Special Session on Power Line Interference (INVITED), International WROCLAW Symposium on Electromagnetic Compatibility, WROCLAW, Poland, 17-19 September 1980. (I)

Boerner, W-M., Cole, J., Olson, D.E., Measurement and Analysis of Controlled VLF Radiation from the EHV-DC Line from Dorsey to Radison, Manitoba and of Related Perturbations of Electric Parameters in Atmo- to Meso-Sphere, (INVITED) VI International Conference on Atmospheric Electricity, IAMAP/ICAE, Manchester, England, July 28 - August 1, 1980. (I)

1981

Boerner, W-M., Jordan, A.K., Kay, I.W., Introduction to the Special Issue on Inverse Methods in Electromagnetics, IEEE Trans. AP 29, March 1981, Guest Editors: W-M. Boerner, A.K. Jordan, I.W. Kay, pp. 185-189. (E)

Boerner, W-M., El-Arini, M.B., Chan, C-Y., Mastoris, P.M., Polarization Dependence in Electromagnetic Inverse Problems, Special Issue on "Inverse Methods in Electromagnetics", IEEE Trans. AP 29 (2), March 1981 (Guest Editors: W-M. Boerner, A.K. Jordan, I. Kay), pp. 262-272. (E/P)

Boerner, W-M., Ho, C-M. and Foo, B-Y., Use of Radon's Projection Theory in Electromagnetic Inverse Scattering, Special Issue on "Inverse Methods in Electromagnetics", IEEE Trans AP 29 (2), March 1981 (Guest Editors: W-M. Boerner, A.K. Jordan, I. Kay), pp. 336-341. (E/P)

Boerner, W-M., Optimal Polarization Concept in Radar Imaging, Proceedings of an ESA-EAR Sel Workshop held in Alpbach, Austria, 16-20 March 1981 (ESA SP-166, May 1981), pp. 129-142 (INVITED). (I/W)

Boerner, W-M., El-Arini, M.B., Optimal Polarization Concept in Electromagnetic Inverse Problems, 1981 International Geo-Science and Remote Sensing Symposium (IGARRS, 81), Washington, D.c., June 8-10, 1981, pp. 1035-1050. (C/S)

Boerner, W-M., et al, Impacts of Solar & Auroral Storms on Power Line Systems, Presented at the Manchester Conference, August 1981, Conference Proceedings published in Space Science Reviews 34 (1983), Published by D. Reidel Publishing Company, Paper No. SSR70-0, pp. 195-205. (I/P)

Boerner, W-M., Use of the Optimal Polarization Concept in Electromagnetic Imaging of Hydrometeor Distribution, Workshop in Precipitation Measurements from Space, NASA, Goddard Space Flight Center, Greenbelt, MD., April 28- May 1, 1981, pp. D-326-340. (W)

Boerner, W-M., Inverse Modeling in Remote Sensing, XXth General Assembly, URSI, Washington, D.C., August 12, 1981 (INVITED: to appear in the International Journal of Remote Sensing, 56 printed pages). (I/W)

Boerner, W-M., El-Arini, M.B., Chan-C-Y., Ip, A., Saatchi, S. and Mastoris, P.M., Polarization Utilization in Radar Target Reconstruction, Technical Report UICC-CL-EMID-NANRAR-Q1, January 15, 1981, Communications Laboratory, Electrical Engineering Department, UIC, P.O. Box 4348, Chicago, IL 60680, (187 pages). (R)

Boerner, W-M., The Importance of the Optimal Polarization Concept in Inverse Problems of Optical and Electromagnetic Imaging (INVITED), 12th Assembly of the Int. Com. for Optics, IOCC 81, Graz, Austria, August 31-September 5, 1981. (I/S)

Boerner, W-M., Ho, C-M., Analysis of Physical Optics Far Field Inverse Scattering for the Limited Data Case Using Radon Theory and Polarization Information, Wave Motion 3, North Holland Publishing Co., Amsterdam, Oct. 1981, pp. 311-333. (P)

Boerner, W-M., El-Arini, M.B., Utilization of the Optimal Polarization Concept in Radar Meteorology, Paper No. 763, Proceedings of the 20th Conference on Radar Meteorology of the American Meteorological Society, November 30-December 3, 1981, Boston, MA., pp. 656-665. (S)

Boerner, W-M., El-Arini, M.B., Saatchi, S., Davidovitz, M., Ip, W.S., Nespor, J.D., Polarization Utilization in Radar Target Reconstruction: Buoy Targets Measured by S. Weisbrod and L.A. Morgan of Teledyne Micronetics, Final Report, CL-EMID, UICC, NARRAR 81-09-15, Communications Lab., Electrical Engineering Dept., UIC, Chicago, IL. 60680, September 15, 1981, (195 pages). (R)

Boerner, W-M., Polarization Characteristics of Near-to-Ground Clutter at Millimeter-to-Near-Millimeter Wavelengths, (Invited), Final Report, Battelle Delivery Order No. 1914, Contract #DAAG 19-76-D-0100, USA-MICOM- DR-SMI-REL, Sept. 30, 1981 (distribution only as directed by MICOM-DRSMI, BCL Durham Operations, or the Army Research Office), 246 pages. (I/R)

Boerner, W-M., Use of Polarization in Electromagnetic Inverse Scattering, Radio Science, Vol. 16, No. 6 (Special Issue including papers: 1980 Munich Symposium on Electromagnetic Waves), pp. 1037-1045, Nov/Dec, 1981. (I/S/P)

1982

Chaudhuri, S.K., Boerner, W-M., Analysis of Internally Reflected Rays in Electromagnetic Scattering by Dielectric Spheroids, (URSI-Comm. B., Boulder, CO., USA), January 13-15, 1982, p. 11. (S)

Boerner, W-M., El-Arini, M.B., Saatchi, S.S., Davidovitz, M., Evaluation of Experimental Data on the Optimal Polarization Properties of Buoy Targets Measured in Free Space and Partially Submerged in Water, (URSI-Comm. B., Boulder, CO., USA), January 13-15, 1982, p. 54. (S)

Chan, C-Y., Boerner, W-M., A Decomposition Theorem for the Power Scattering Matrix of Radar Targets, (URSI-Comm. B., Boulder, CO., USA) January 13-15, 1982, p. 55. (S)

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Boerner, W-M., Mirmira, V.K.S., Manson, A.C., Yang, C-W., Buti, A.K., Electromagnetic Reconstruction Techniques, Proceedings of SPIE, Vol. 358 (Applications of Mathematics in Modern Optics), August 1982, pp. 143-148. (S)

Boerner, W-M., Polarization Control in Radar Meteorology, (invited), Presented at the URSI Open Symposium, Multiple-Parameter Radar Measurements of Precipitation, Bournemouth, U.K., (preprints available), 22 printed pages, August 1982. (I/W)

Boerner, W-M., Inverse Scattering in Electromagnetics, Presented at the Research Techniques in Wave Propagation & Scattering Workshop/Symposium, Sponsored by OSU, ARO, ONR, (Invited Base Lecture), October 1982. (I/W)

Boerner, W-M., Mirmira, V.K.S., Manson, A.C., Yang, C-W, and Buti, A.J., Extensions of Radon's Projection Theory in Radar Target Shape Reconstruction, Workshop on "Research & Development to New Procedures in NDT", Workshop Preceedings published by Springer Verlag, Aug/Sept. 1982, pp. 413-424. (I/W)

Boerner, W-M., Inverse Modeling in Remote Sensing, Ohio State University Workshop/Symposium on "Research Techniques in Wave Propagation and Scattering", Oct. 18-21, 1982. (I)

1983

Davidovitz, M. and Boerner, W-M., Extension of Kennaugh's Polarization Null Theory of the Monostatic Reciprocal Scattering Matrix to the Bistatic Non-symmetrical and/or Non-reciprocal Monostatic Scattering Matrix Cases, IEEE Trans. AP-30, in print. (P)

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Boerner, W-M., Radar Target Classification Using Polarimetric Downrange Signatures, Proceedings of the Second Workshop on Polarimetric Radar Technology, U.S. Army Missile Command, Redstone Arsenal, AL, May 3-5, 1983, published by GACIAC/IIT Research Institute, 10 W. 35th St., Chicago, IL 60616, Rept. No. PR 83-01, May 3-5, 1983, p. 181-240. (I/W)

Hansen, A.L., Boerner, W-M., A Polarization Radar Design Study for Clutter Suppression and Target Enhancement, Proceedings of the Second Workshop on Polarimetric Radar Technology, U.S. Army Missile Command, Redstone Arsenal, AL, May 3-5, 1983, published by GACIAC/IIT Research Institute, 10 W. 35th St., Chicago, IL 60616, Rept. No. PR 83-01, May 3-5, 1983, pp. 241-250. (I/W)

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1984

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Nespor, J.D., Agrawal, A.P., Boerner, W-M., Development of a Model-Free Clutter Description Based on a Coherency Matrix Formulation, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Saatchi, S.S. and Boerner, W-M., Error Analysis of Radar Scattering Matrix Measurements, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Lempkowski, R.B., and Boerner, W-M., A Modular Testbed Design of a High Resolution Polarization Radar for Target in Clutter Detection and Description, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Huang, X-Q. and Boerner, W-M., Lambert, Mollweide and Aitoff Projections of the Polarization Sphere and its Applications to Radar Polarimetry, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Manson, A.C. and Boerner, W-M., A Classification Analysis of High Resolution Polarimetric Target Downrange Signatures Based on Kennaugh's Polarimetric Target Characteristic Operator Theory, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Khounsary, A.M. and Boerner, W-M., Polarimetric Radiative Transport Description of Propagation Through Ensembles of Discrete Homogeneous Scatterers in an Inhomogeneous Medium, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Yang, C-Y., James, B.D., and Boerner, W-M., Extension of Scalar to Tensorial Diffraction Tomography for Analyzing Faraday Rotation Effects, to appear in the Proceedings of the 1984 International IEEE/AP-S Symposium and National Radio Science Meeting at Copley Place, Boston, June 25-28, 1984. (I/C)

Short Courses given by W-M. Boerner and Associates on

BASIC & ADVANCED RADAR POLARIMETRY AND ITS APPLICATIONS TO NON-COOPERATIVE TARGET IN CLUTTER DETECTION, DISCRIMINATION, CLASSIFICATION, IMAGING AND IDENTIFICATION to

Westinghouse Friendship International Airport P.O. Box 746, MS 1105 Baltimore, MD 21203	One Day Course Aug. 2, 1983
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Eglin Air Force/AFATL-DLMT Eglin AFB, FL 32542	One Day Course Aug. 3, 1983
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Sperry Research Center Electronic Systems Division 100 North Road Sudbury, MA 01776	Two Day Course Feb. 1982 One Day Course Sept. 1981
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McDonnell Douglas Research Laboratory Electromagnetics Division P.O. Box 516 St. Louis, MS 63166	One Day Course June 1981
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Scientific Atlanta Instrumentation Division P.O. Box 105027 Atlanta, GA 30348	One Day Course June 1983
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SPC Technologies, Inc. Technology Division 1500 Wilson Blvd. Arlington, VA	One Day Course June 1982
ITT Gilfillan Systems Analysis Group 7821 Orion Avenue Van Nuys, CA 91409	One Day Course May 1982
Enterprise Electronic Corp. Radar Meteorology Division 5801 Lee Highway Arlington, VA 22207	Two Day Course Sept. 1982
Schlumberger-Doll Res. Center Geo-Electromagnetic Sounding Div. Old Quarry Road P.O. Box 307 Ridgefield, CT 06877	Two Day Course March 1982
Raytheon Company Missile Systems Division Advanced Systems Center Bedford, MA	One Day Course Feb. 1982
Bell Aerospace Textron Advanced Systems Division P.O. Box 1 Buffalo, NY 14240	Two Day Course May 1982
Boeing Aerospace Company Kent Space Center Engineering Technology Division Multi-sensor Radar Section P.O. Box 3999 Seattle, WA 98124	Two Day Course June 1982 One Day Course Sept. 1982 Feb. 1983 Oct. 1983
Martin Maretta P.O. Box 5837, MP 304 Orlando, FL 32885	One Day Course Aug. 4, 1983
General Dynamics Convair Division 5001 Kearney Villa Road San Diego, CA 92123	Two Day Course Aug. 16-17, 1983
General Dynamics Pomona Division P.O. box 2507 Pomona, CA 91769	Two Day Course Aug. 18-19, 1983
TRW, Inc. Defense & Space Systems 1619 3rd. Street Manhattan Beach, CA 90266	Two Day Course Dec. 14-15, 1983

Boeing Military Airplane Co.
3801 S. Quincy St.
Wichita, KS 67277

One Day Course
Dec. 16, 1983

Honeywell
Aerospace & Defense Group
Systems Research Center
2600 Ridgway Parkway
Minneapolis, MN 55440

Two Day Course
Jan. 19-20, 1984

Hughes Aircraft Company
Space & Communications Group
Space Sensors Laboratory
El Segundo, CA

One Day Course
Spring 1984

General Electric Co.
Military Electronics Systems
Advanced Development Engineering
Syracuse, NY 13221

Two Day Course
Spring 1984

CHAPTER V

V.INTERACTION WITH DoD/NATO RESEARCH LABORATORIES, NATIONAL/NATO RADAR INDUSTRIES, AND UNIVERSITY RESEARCH CENTERS

A vitally important contribution to the research efforts of the ARO-Electronics Division is the National and NATO interactions carried out under this contract.

- A. Interaction with US DoD/Government University Laboratories
 - A.1 US DoD Research Facilities
 - US Army Commands
 - US Naval Research Centers
 - US Air Force Technical Laboratories
 - US Defense Advanced Research Project Agency
 - A.2 US Governmental Research Facilities
 - NASA-Research Centers
 - NOAA-Research Centers
 - A.3 University Research Centers
- B. Interaction with National Industrial Research & Development Centers
- C. Interaction with NATO-Member Countries
 - C.1 NATO Grants/Awards
 - C.2 NATO/DoD/Governmental Laboratories
 - C.3 NATO/Industrial Research & Development Centers
 - C.4 NATO/University Research Laboratories
 - C.5 Austral-Asian Pacific Collaboration

A. Interaction with US DoD Government University Laboratories

A.1 US DoD Research Facilities

(Note: Research lectures, shortcourses, etc. presented are not listed.)

US ARMY Commands

Research Lab	Contact	Topic
MICOM/DRSME-REG Redstone Arsenal	Mr. Lloyd W. Root (205) 876-8131	Polarization Characteristics of Clutter at m-to-mm wavelengths
MERADCOM Ft. Belvoir	Dr. Karl Steinbach (703) 664-4970	Electromagnetic Deep Sounding for Detection and Imaging of Mines and Buried Objects.
ERADCOM DELCS	Dr. Vahakn Nalbandian (201) 544-5146 Mr. William Fischbein (201) 544-5218	Development of Detection & Classifi- cation Algorithms for Military Ground-Based Stationary Targets Em- bedded in Ground & Tropospheric Clutter Utilizing High-Resolution Polarimetric Radar Data Collected with ERADCOM-DELCS-R-T Polarization Radars
Adelphi-DRDEL	Mr. John Johnson (202) 394-3585	
SENCOMS	Dr. Felix Schwerling (201) 544-4812	Polarization Characteristics of m-to-sub-mm Wave Propagation Paths
DRSMC LCA	Dr. Andrew Hunton (201) 724-4718/3801	Detection of General Vector of Target Motion Using Polarimetric Doppler Data
SCA	Dr. Jeffreys Heberley (201) 724-6255	Application of High Resolution Radar Polarimetry
DELAS-AR-A Atm. Sci. Lab	Dr. Douglas R. Brown (505) 678-3691	Polarimetric Radar Meteorology
WRMC	Dr. Larry E. Larsen (202) 576-3615 (301) 427-5125	Sub-aquatic microwave propagation tomography

US NAVAL Research Centers

Research Lab	Contact	Topic
NRL	Mr. Jack Daley (202) 767-2241	Radar Polarimetry
	Dr. Dennis Trizna (202) 767-4873	Polarimetric Radar Analysis of Sea Scatter
	Dr. Arthur K. Jordan (202) 767-6609	Electromagnetic Inverse Problems
	Dr. Meril Skolnik (202) 767-4873	Advancement of Radar Polarimetry
	Dr. Bernard Lewis (202) 767-3644	Polarimetric Sea Scatter Analysis
	Dr. Lewis D. Wetzel (202) 767-3417	High Resolution Radar Polarimetric Sea Scatter Analysis
	Dr. Lothar Ruhnke (202) 767-2951	Polarimetric Doppler Radar Meteorology
NWC	Mr. Brett H. Borden (619) 939-3962	Radar Polarimetry in Electromagnetic Inverse Problems
	Dr. Guenter Winkler (619) 939-2970	Radar Polarimetry/Inverse Techniques
	Dr. Robert Dinger	Polarization Radar Techniques for Glint Suppression
	Dr. David Reade (619) 939-3531	High Resolution Radar Polarimetry
NSWC	Dr. Bruce Z. Hollmann (703) 663-8057	Radar Polarimetry in Electromagnetic Inverse Problems
NOSC	Dr. Donald Wehner (619) 225-6649/7838	Radar Polarimetry in Electromagnetic Inverse Problems
	Dr. Juergen Richter (619) 225-7919	Radar Polarimetric Analysis of the Ocean Marine Boundary Layer
NADC	Dr. Otto Kessler (215) 441-1569	High Resolution Radar Polarimetry: Theory/Metrology/Imaging
	Mr. Ray Dalton (215) 441-2306	Radar Target Classification Algorithm Development
NPGS	Dr. Michael Morgan (408) 646-2677/2082	Radar Polarimetry in Electromagnetic Inverse Problems
NPMTIC	Dr. Dean Mensa (805) 982-8885/6	High Resolution Polarimetric Radar Imaging

US Air Force Technical Laboratories

Research Lab	Contact	Topic
RADC Rome, N.Y.	Mr. Vincent C. Vannicola (315) 330-4437 Mr. Daniel Tauroney (315) 330-4441	Polarization Vector Signal Processing Monostatic and Bistatic Radar Polarimetry
AFAL Dayton, OH	Mr. Medhi Shirazi (513) 255-6427	Polarimetry Radar Signature Analysis
AFATL Eglin AFB	Dr. Max McCurry (904) 882-4631 Dr. James McLaughlin (904) 882-4634	Polarimetric Radar Metrology Polarimetric Radar Signal Analysis
AFWL Kirtland, AFB	Dr. Carl Baum (505) 844-9816	Polarimetric Radar Target Resonance Descriptions
DARPA	Colonel Juergen Gobien (202) 694-2612	Polarimetric Radar Target Classification/Identification
MITRE	Dr. Nicolas Tomljanovich (617) 271-2000 Dr. Richard Weiss (617) 271-2000 Ext.2954 Dr. M. Robert Dresp (617) 271-2000 Ext.7607	Electromagnetic Inverse Problems Utilization of Radar Polarization Signatures in Target Identification Ionospheric Inversion Problems Satellite Communications
MIT-Lincoln Labs	Dr. Leon J. Ricardi (213) 643-0869 Dr. R. Alexander Ross (617) 862-5500 Dr. Gregory E. Heath (617) 862-5500 Ext. 2815 Mr. Rick Barnes Dr. Gerald Morse (617) 862-5500 Ext. 3447	Polarization Phased Antenna Array Design Radar Target Identification Bistatic Scattering Matrix Analysis Radar Target Identification Based on High Resolution Radar Polarimetric Data

A.2 US Government Research Facilities

NASA Goddard, SFC	Dr. David Atlas (301) 344-6925	Polarimetric Radar Meteorology
Wallops FF	Dr. Charles Vaughn (804) 826-3411 Ext. 653	Radar Tracking of Birds & Insects
NOAA NSSL	Dr. Richard Doviak Dr. Dusan S. Zrnic (405) 360-3620	Polarimetric Radar Meteorology Polarimetric Doppler Radar Analysis
ERL-WPL	Dr. Fausto Pasqualluci (303) 497-6207	Polarimetric Radar Meteorology
NCAR	Dr. Robert Serafin (303) 494-5151	Polarimetric Radar Meteorology

A.3 US University Associated Research Centers

Electro-Science Laboratory
Ohio State University
1320 Kinnear Road
Columbus, OH 43212

Dr. David L. Moffatt
(614) 422-5749
Dr. Jonathan D. Young
(614) 422-6657

Environmental Research Institute
of Michigan
3300 Plymouth Road
P.O. Box 8618
Ann Arbor, MI 48107

Dr. Richard Larson
(313) 994-1200 Ext. 237

Dr. Demetrios T. Politis
(313) 994-1200 Ext. 388

Wave Propagation Laboratory
University of Washington
Dept. of Electrical Engr., FT-10
Seattle, WA 98195

Dr. Akira Ishimaru
(206) 543-2169/2150

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, GA 30332

Mr. Jerry L. Eaves
Dr. William A. Holm
(404) 424-9609
Dr. Otto E. Rausch

Electromagnetics Research Lab
Dept. of Electrical Engineering
University of Illinois
1406 W. Green St.
Urbana, IL 61820

Dr. Georges A. Deschamps
(217) 333-2064
Dr. Yuen-Tze Lo
(217) 333-0293

Electromagnetics Division
IIT-Research Institute
10 W. 35th St.
Chicago, IL 60616

Dr. Allen Taflove
(312) 567-4490
Dr. Ted Martin
(312) 567-4486

Remote Sensing Center
Texas A&M University
College Station, TX 77843

Dr. Buford Randall Jean
(409) 845-5203

Remote Sensing Laboratory
University of Kansas
2291 Irving Hill Road
Lawrence, KS 66044

Dr. Richard K. Moore
(913) 864-4836
Dr. Adrian K. Fung
(913) 864-4832

Lawrence Livermore National Labs
University of California
Electronics Engr. Department
P.O. Box 5504
Livermore, CA 94550

Dr. Robert M. Bevensee
(415) 422-6787

Dr. Ray J. King
(415) 423-2369

B. Industrial R & D Centers

Sperry Research Center
100 N. Road
Sudbury, MA 01776

Dr. C. Leonard Bennett
(617) 369-4000 Ext. 297

Bell Aerospace Tektronix
P.O. Box 1
Buffalo, NY 14240

Dr. Lionel Shub
(716) 297-1000

Raytheon Company
Hartwell Rd., Systems Bldg.
Bedford, MA 01730

Dr. Edwin R. Hiller
(617) 274-7100 Ext. 2601

McDonnell Douglas
Research Laboratory
Electromagnetics & Radar Div.
Box 576, Bldg. 110
St. Louis, MS 63166

Dr. Louis N. Medgyesi-Mitschang
(314) 233-2504
Dr. J. Carl Leader
(314) 233-2503
Dr. Cornel Eftimiu
(314) 233-2501

Boeing Aerospace Co.
Kent Space Center
Engineering Technology Div.
68th Ave. S., Mail Stop
06-09/Bldg 18-12
Kent, WA 98301

Mr. George Swetnam
(206) 773-5043/0326
Dr. Herbert A. Williams
(206) 773-2303
Dr. Ray H. West
(206) 773-0162

The Bendix Corporation
43 Williams Ave. / MC 2/17A
Teterboro, NJ 07608

Dr. James Schuchardt
(201) 393-3397

The Bendix Corporation
400 Beiger Street
Mishawaka, IN 46544

Mr. John Gannaway
(219) 255-2111

Westinghouse Defense & Space Center
Friendship International Airport
Baltimore, MD 21203

Dr. Robert Raven
(301) 765-6331
Mr. Norman Powell
(301) 765-6331/7144

Martin Marietta
Aerospace Division
Radar Systems Development
P.O. Box 5837, MP 72
Orlando, FL 32055

Dr. George M. Green
(305) 352-3612

General Dynamics
5001 Kearney Villa Road
San Diego, CA 92123

Dr. George Mavko
(619) 277-8900
Dr. Gus Tricoles
(714) 692-7350

Sperry Electronics Systems
P.O. Box 4648, M/S-231
Clearwater, FL 33518

Dr. David R. Wakeman
(813) 577-1900 Ext. 3119

General Dynamics
P.O. Box 2507
Pomona, CA 91769

Dr. Hans-P. Schmid
(714) 620-7511 Ext. 3743

Boeing Military Airplane Co.
P.O. Box 7730/MS K-75-65
Wichita, KS 67277

Dr. Kenneth Rogers
(316) 526-2681

TRW, Inc., Defense & Space Sys.
1619 3rd Street
Manhattan Beach, CA 90278

Dr. Daniel Carpenter
(215) 535-3147

General Electric Co.
Space Research Center
P.O. Box 8555
Philadelphia, PA 19101

Dr. Adolph E. Buescher, Jr.
(215) 962-2396/7

General Electric Co.
Military Electronics Sys. Oper.
Advanced Development Engr.
ADE/MESO, Bldg 4 Rm 5
Syracuse, NY 13221

Dr. Richard D. Taylor
(315) 456-7442

Honeywell Research & Electronic
Systems Division
P.O. Box 312, Code MN 17-2354
Minneapolis, MN 55440

Dr. Raja Suresh
(612) 378-4579
Dr. L. James Marier, Jr.
(612) 931-5835

Scientific Atlanta
3845 Pleasantdale Road
Atlanta, GA 30390

Dr. Doren Hess
(404) 925-5655
Mr. Gerald Hickman
(404) 441-4210

Global Analytics, Inc.
10065 Old Grove Road
San Diego, CA 92131

Dr. Steven Weisbrod
(619) 2260

Northrop Corporation
600 Hicks Road
Rolling Meadows, IL 60008

Dr. Oscar Döchler
(312) 259-6000

Raytheon Company
Communications Systems Lab.
Metropolitan Corporation Center
Bldg. 2, M/S-380, Glen Road
Marlborough, MA 01752

Dr. C. Leonard Bennett
(617) 481-5910
Ext. 6356/6002

Hughes Aircraft Corporation
Technology Division
El Segundo, CA 90278

Dr. K.C. Lang
(213) 648-2089

Defense Systems Inc.
6804 Poplar Place
McLean, VA 22102

Dr. Henry W. Mullaney
(703) 442-9636

C. INTERACTION WITH NATO-MEMBER COUNTRIES

C.1 Grants/Awards

NATO-Grant No. 1405 Resolving Power in Broadband Microwave Imaging Systems with: FHP-FGAN Wachtberg-Werthhoven Dr. Klaus Krücker Dr. Klaus Magura HF Engineering Labs Inst. HF-Technology Universität Erlangen-Nürnberg Prof. H. Brand/Prof. H. Ermert	July 15, 1977-July 15, 1981 (including extensions) Total Amount \$12,000.00
NATO-IMOR-Senior Scientist Fellowship on Advancement of High Resolution Radar Polarimetry with: SHAPE-TC Sensors Branch Command Control & Systems Div. Scheveningen, The Hague Dr. Andre J. Poleman	April 15, 1981-April 15, 1984 Total Amount \$5,000.00 (application for extension submitted)
NATO-ARW Grant for NATO-ARW-IMEI-1983, Bad Windsheim, FRG, Sept. 18-24, 1983 with: DFVLR/HFT Division Dr. Martin Vogel	April 15, 1982 continued Total Amount \$25,000.00
US Army ARO, European Branch Workshop Grant with: DFVLR-OPH Dr. Martin Vogel	April 1983, continued Total Amount \$3,000.00
DFVLR Conference Contribution for NATO-ARW-IMEI-1983 Dr. Wolfgang Keydel	August 1983, continued Total Amount \$DM 20,000.00
Government of the Netherlands Distinguished Visiting Professor Prof. Antoon DeHoop	September 1976 to September 1980
DFVLR-OPH Distinguished Scientist Lectorships Dr. Wolfgang Keydel	July 1981 to July 1983
NTNF-Kjeller Norway Visiting Scientist Fellowship Dr. Dag. T. Gjessing	September 1981 & June 1982
RSRE-Malvern, UK Visiting Scientist Fellowship Dr. Chris Baynham	August, 1982
BMVg-Bonn, FRG Visiting Scientist Fellowship Dr.-Ing Rolf Theissinger	December 1983

C.2 NATO-DOD/Governmental Labs

SHAPE Technical Centre Sensor Systems Division P.O. Box 174 2501 CD The Hague Netherlands	THREE DAYS (Semi-Annual)	Mr. William F. Ashton Dr. Andre J. Poelman 31=70-245550 Ext.457
German Aerospace Research Establishment DFVLR-HF Technology Division DFVLR-Oberpfaffenhofen D-8031 Post Wessling/Obb. FR Germany	TWO DAYS (Semi-Annual)	Dr. Wolfgang Keydel 49=8153-28-305
Research Establishment for Applied Science FGAN-Forschungs Institut für HF- Physik König-Str 2 D-5307 Wachtberg-Werthhoven FR Germany	ONE DAY (Semi-Annual)	Dr. Klaus Krücker 49=228-8521 Dr. Christoph v. Winterfeld 49=228-852-235 Dr. Heinrich Gniss Dr. Klaus Magura 49=228-852-239
OSCA, SACEUR Science & Technology Command B-7010 SHAPE, Mons Belgium	ONE DAY December 1981	Dr. Tilo Kester 32=6544 5512 32-2687-66-36
ARO/ONR European Branch Offices Edision House Old Marylebone Road London, UK	ONE DAY August 1982	Capt. M.A. Howard 44-1629-9272 Ext. 4869
NATO Headquarters NATO, Scientific Affairs Division ASI-ARW Programs B-1110 Bruxelles Belgium	2 Visits/yr	Dr. Mario DiLullo Dr. Craig Sinclair 32=2241-00-40 Ext. 2198
Royal Institute for Industrial Research Royal Norwegian Government Forskningsv. N.1, P.O. Box 350 Blindern, Oslo 3 Norway	ONE DAY Sept. 1981 June 1982	Dr. Hans Pedersen 47=2-695880
Environmental Surveillance Techn. Program, Royal Norwegian Council for Scientific & Industrial Research P.O. Box 25 N-2007 Kjeller, Norway	ONE DAY Sept. 1981 June 1982	Dr. Dag T. Gjessing Mr. Terje Lund 47=2-712-660

Headquarters Norwegian Defense Research Center P.O. Box 25 N-2007 Kjeller, Norway	ONE DAY June 1982	Dr. Karl Holberg 47-2-535603
Royal Signals & Radar Estab. Radar Electronics Division St. Andre// Road Great Malvern, Wores WR 14 3PS UNITED KINGDOM	ONE DAY August 1982	Dr. Chris Baynham Dr. Steven Gibbs Dr. Shane Cloude Dr. Edward Pike 44-6845-2733
Ministry of Defence and War Admiralty Surface Weapons Establishment Electromagnetic Sensors Division Cosham, Portsmouth United Kingdom	ONE DAY August 1982	Dr. Roderick M. Logan 44-705-379411 Ext. 2136
TNO-Physisch Laboratorium Microwave Division P.O. Box 96864 2509 JG, The Hague The Netherlands	ONE DAY Sept. 1983	Dr. Hans Sittrop 31-70-26-4221
CSIRO, Division of Radio Physics Antenna & Electromagnetics Div. Radioastronomy Section P.O. Box 76 EPPING, NSW 2121 Australia	THREE DAYS August 1978	Dr. John D. Hunter (moved to Measure- ment Standards Laboratory/CSIRO)
Canada Centre for Remote Sensing Radar and Electronics Division 2464 Sheffield Road Ottawa, Ont. KIA 0S4	ONE DAY Oct. 1980 March 1981	Dr. R.K. Raney (613) 593-4457
National Research Council of CAN Electromagnetic Engr. Section Div. of Electr. Engineering Montreal Research Laboratory Ottawa, Ont KIA 0R8	TWO DAYS Oct. 1980 March 1981	Dr. Glenn C. McCormick (902) 532-2684 Dr. R. Allan Hurd (613) 596-9395
Canada Communications Res. Center Space Electronics, Radar Division Shirley Bay, P.O. Box 11490, Street H Ottawa, Ont K2H 852	TWO DAYS March 1981	Dr. Robert W. Breithaupt Dr. Roger E. Barrington (613) 596-9395
European Space Agency Systems Engineering Department Radar Sensors in Remote Sensing Pomeinweg, Noordwijk The Netherlands	ONE DAY Sept. 1983	Dr. Georg Graf 31-1719-86555

Physikalisch-Technische
Bundesanstalt, Elektrische
Messtechnik, Radar und Wellen
Bundesallee 100
D-3300 Braunschweig
FR Germany

ONE DAY
Dec. 1981

Dr. Volkmar Klose
49=531-592-22 40

Max Planck Institut für Radio
Astronomie
(Radio -Teleskop Effelsberg)
Auf dem Hügel 69
D-5300 Bonn 1
FR Germany

ONE DAY
April 1981

Dr. Rolph Wohlleben
49=228-525 322/19

Max Planck Institut für Aeronomie
Space Radar Scatterometry
Postfach 20
D-4311 Katlenburg-Lindau 3
FR Germany

ONE DAY
Dec. 1981

Dr. Ray Greenwald
(has moved to the US
in the meantime)

C.3 NATO-Industrial R & D Centers Visited

THORN-EMI Electronics Ltd
Electronic Systems Division
Wells, Somerset Wookey Hole Road
England BA 5 1AA

ONE DAY
June 1982
August 1982

Mr. Leonard A. Cram
44=749-72081
Ext. 209

MARCONI
Research Laboratory
Great Baddow
Chelmsford/Essex
UNITED KINGDOM CM2 8HN

ONE DAY
August 1982

Dr. J.F. Skwirzynski
Dr. S. Rotheram
44=245-73331
Ext. 58

TELEFUNKEN-AEG
Electronic Systems Division
Sedan-Str. 10
D-7900 ULM
FR Germany

TWO DAYS
June 1982

Dr. Donald Stock
49=731-1920

BRITISH AEROSPACE CORP.
Radar Electronics Division
Warton, Lancashire PR-1AX
United Kingdom

ONE DAY
August 1982

Dr. Brian Barber
44=252-24461
Dr. Ronald A. Evans

SIEMENS, A.G.
Medical Division
Tomographic Imaging
Henke-str. 127
D-8520 Erlangen
FR Germany

ONE DAY
April 1983

Dr. Werner Haas
Dr. Manfred Pfeiler
49=9131-84-1

SIEMENS A.G.
Radar Electronics
SIFR Ort PE3
Hoffmann- str. 51
D-8000 München 70

ONE DAY
DEC. 1983

Dr.-Ing Otto Albersdörfer
49=89-722-22829

C.4 NATO University Research Laboratories

Applied Electromagnetic Lab Dept. of Electrical Engineering University of Manitoba Winnipeg, Man. R3T 2N2 CANADA	ONE ANNUAL VISIT	Prof. Lotfallah Shafai (204) 474-9615 Dr. Ram M. Mathur (202) 474-9603
HF Engineering Laboratory Institut für HF-Technik Universität Erlangen-Nürnberg Cauerstr. 9, D-8520 Erlangen FR GERMANY	TWO ANNUAL VISITS	Prof. Dr.-Ing. Hans Brand 49=9131-857215 Prof. Dr-Ing. Helmut Ermert 49=9141-85214
Electromagnetic Research Lab Dept. of Electrical Engineering Delft Technical University P.O. Box 5031 2600 GA Delft THE NETHERLANDS	ONE ANNUAL VISIT	Prof. Antoon De Hoop Prof. Hans Blok 31=15-566311
Microwave Research Institute Technical University München Institut f. Mikrowellentechnik Arcisstr. 21 D-8000 München 2 FR GERMANY	ONE ANNUAL VISIT	Prof. Horst Groll 49=89-2105-8389 Prof. Jürgen Detlefsen 49=89-2105-8389
Applied Optics Laboratory Dept. of Applied Physics State University of Groningen Nijenborgh 18, NL-9747 AG Groningen THE NETHERLANDS		Prof. Hedzer Ferwerda 31=50-115959
Laboratoire de Physique Mathématique Université des Sciences et Techniques du Languedoc Place Eugene-Bataillon F-34060 Montpellier Cedex FRANCE	ONE ANNUAL VISIT	Prof. Pierre C. Sabatier 33=67-544850
Group D'Electromagnétisme Lab. des Signaux et Systemes CNRS-ESE F-91190 GIF-SUR-YVETTE FRANCE	ONE ANNUAL VISIT	Prof. Walid Tabbara 33=6-941-8040

H.H. Wills Physics Laboratory University of Bristol Royal Fort, Tyndall Ave. Bristol BS8 1TL UNITED KINGDOM	ONE DAY June 1982	Prof. Michael E.R. Walford 44=272-24161, ext. 434
---	----------------------	--

Electrophysics Laboratory Inst. f. Fysikalsk Electronikk Universitetet i Trondheim 7034 Trondheim - NTH NORWAY	ONE DAY June 1982	Prof. Andreas Tønning
--	----------------------	-----------------------

Applied Physics Lab/Optics Div. Universität Erlangen-Nürnberg Erwin Rommel Str. 1 D-8520 Erlangen FR GERMANY	ONE ANNUAL VISIT	Prof. Adolf Lohmann 49=9131-857408
--	---------------------	---------------------------------------

C.5 Austral-Asian Pacific Collaboration

(Note: during the period of 1970 to 1984, all of the scientists herein mentioned, either visited our laboratory, or we theirs.)

School of Radar Studies Department of Electrical & Electronics Engrn. Indian Institute of Technology - Dehli Hauz Khas, New Dehli 110029 India	Prof. P.V. Inderesen Prof. Rajendra K. Arora
--	---

Applied Electromagnetics & Remote Sensing Lab Department of Electrical Engineering IIT - Kanpur Kanpur, U.P. 208016 India	Prof. Naresh C. Mathur
---	------------------------

Communications Laboratory Department of Electronics & Communications Indian Institute of Science Bangalore, Malleswaram 560012 India	Mrs. Prof. R. Chatterjee Prof. A.P. Kumar
--	--

Radar Engineering Laboratory Department of Electrical Engineering University of Singapore Prince Edward Road Singapore 2	Prof. J. W-Y. Chen Prof. P.S. Kooi
--	---------------------------------------

Applied Mathematics Laboratory Research School of Physical Sciences Australian National University Cambera, A. CT.	Prof. Allan W. Snyder
---	-----------------------

Radar Meteorology Laboratory
Meteorology Department
University of Melbourne
Parkville, Vic.
3052 Australia

Prof. Udo Radok

Division of Radiophysics
CSIRO
P.O. Box 75
Epping, NSW
2121 Australia

Prof. Dr. J.P. Wild
Dr. Peter Thomas

Radio Glaciology Laboratory
Antarctic Division
Department of Science
568 St. Kilda Road
Melbourne, Vic.
3004 Australia

Dr. W.F. Budd

Radio Science Laboratory
Electrical Engineering Department
University of Auckland
Auckland, New Zealand

Prof. Donald V. Otto

Remote Sensing Center
Physics & Engineering Laboratory
DSIR, Lower Hutt
New Zealand

Dr. M.J. McDonnell

Electro-Optical Imaging Laboratory
Department of Electrical Engineering
University of Canterbury
Christchurch 1 New Zealand

Prof. Richard H.T. Bates
Prof. Peter T. Gough

Space Architecture Laboratory
Department of Architecture
University of Hong Kong
Hong Kong

Prof. Kuo-Chun Lye

Radio Physics Laboratory
The University of Electro-Communications
1-5-1, Chofugaoka, Chofu-Shi
Tokyo, Japan

Prof. Takeo Yoshino

Communications Laboratory
Department of Electrical Engineering
Tokyo Kogyo Daigaku
Tokyo Institute of Technology
O-Okayama, Meguro-Ku
Tokyo, 152 Japan

Prof. Toshio Sekiguchi
Prof. Kunohiro Suetake

Radio Science & Antenna Laboratory
Faculty of Engineering
Tohoku University
Sendai
980 Japan

Prof. Yasuto Mushiake

Antenna Laboratory
Institute of Applied Physics
University of Tsukuba
Sakura - Ibaraki
305 Japan

Prof. Kyohei Fujimoto

Radio Research Laboratories
Ministry of Ports & Telecommunications
4-2-1 Nukuikita-machi, Koganei-shi
Tokyo 184 Japan

Dr. Tomohiro Oguchi

Electronics Equipment Laboratory
Toshiba Research & Development Center
i, Komukai, Toshiba-cho
Kawasaki 210 Japan

Dr. Kiyoshi Nagai
Research Fellow & Director

CHAPTER VI

VI. DEVELOPMENT OF THE RESEARCH FACILITIES AND MANPOWER
OF UIC-EECS-CL-EMID/GEMSD

The research is carried out in the facilities of the Communications Laboratory/-EECS-UIC and by its staff as described below. For details of space, floor/room arrangements and campus location, we refer to the attached stereoscopic campus view and map, and to the floor plans.

VI.1 Science & Engineering Offices Building (631): 851 S. Morgan Street
Electrical Engineering and Computer Science Department: SEO 11th Floor

Academic staff/teaching offices are located in this 13-story building. For the purpose of consolidating our research efforts, the Office of the Communications Laboratory (SEO-1139 and 1140) will be transferred to building #607, Science and Engineering Laboratories (SEL) 4210 in the near future.

Room SEO-1139 312/996-0195	Mrs. Deborah A. Foster, Administrative Secretary Ms. Nelly Finkelberg, Word Processor (TEMPORARY)
Room SEO-1140 312/996-0195	Research Project Coordinator (to be appointed) Ms. Jean Jones, Secretary (TEMPORARY)
Room SEO-1141 312/996-5489	Dr. Wolfgang-M. Boerner, Professor & Director Academic Staff/Teaching

VI.2 Science & Engineering Laboratories Building (607): 840 W. Taylor Street
COMMUNICATIONS LABORATORY, ROOF TOP ANTENNA RANGE RESEARCH FACILITIES.

The research facilities and research staff offices of the Communications Laboratory are housed on the 4th floor, westward side of the southwest section of the Science & Engineering Laboratories Building #607, SEL-4209, 4210, 4211. In addition, the adjoining balconies on the south and west sides of SEL-4210 and the hallways belong to the Communications Laboratory providing a total of about 9,000 square feet of floor space (see campus view and maps). Provisions for seminar/-lecture/workshop presentations and meetings (overhead and slide projector, blackboard, drawing table, workbench, one complete chemical/physical laboratory experimentation station including water, gas, oxygen, nitrogen, electrical outlets), and extensive electric power outlets for laser, radar experimentation and computer processing are available. At the southside of SEL-4210, a spacious, open balcony is available with straight line-of-sight propagation path of 3km length toward the research building of the Illinois Institute of Technology-Research Institute, and a 1km propagation path in the westward direction toward the University of Illinois-Medical Center to be utilized for polarimetric, radiometric air quality control studies in the future.

The DEC-VAX 11/750 and 11/780 Research Processing Computer is installed in room SEL-4210 F with elevated cable flooring, separate cooling and an environmental (Trane Sentinel) monitoring and control unit which is connected to the UIC permanent equipment monitoring security system of its Maintenance & Operations Center in UIC Building 611.

<u>LAB SEL-4210 (A-H)</u>	<u>Senior Research & Computer Staff (2,800 sq. ft.)</u>
312/996-5140/0195	Mr. Richard Foster, Laboratory Supervisor
<u>Room SEL-4210 A</u>	Laboratory Office
312/996-0195/5140 5489/5284	Mrs. Deborah A. Foster, Administrative Secretary Ms. Jean Jones, Secretary (235 sq ft.)
<u>Room SEL-4210 B</u>	Staff Office: Assoc. Research Engineer/Scientist
312/996-5140	Dr. Sujeet K. Chaudhuri, (Jan.-Dec. 1984)
<u>Room SEL-4210 C</u>	Staff Office: Research Professor & Director
312/996-5489	Dr. Wolfgang-Martin Boerner
<u>Room SEL-4210 D</u>	Staff Office: Computer Operating Engineer
312/996-5284	Mr. Anthony C. Manson
<u>Room SEL-4210 E</u>	Staff Office: Ass't Research Engr./Scientist
312/996-5140	Dr. Ted C. Lee (Jan.-Dec. 1984)
<u>Room SEL-4210 F</u>	DEC-VAX 11/750 & 780 Research Computer System
312/996-5284	DEC-NET, Array Processors & Accessories
<u>Room SEL-4210 G</u>	Report & Documentation Processing Office
312/996-0195	Ms. Nelly Finkelberg, Word Processorist
<u>Area SEL-4210 H</u>	Reception Desk and Laboratory supervisor
312/996-5284/5410 5489/0195	Mr. Richard Foster, Laboratory Supervisor Receptionist, (To be appointed)
<u>Outdoor Balcony South</u>	Radar balcony for outdoor propagation path analyses (UIC <-> IIT-RI): (625 sq ft.)
<u>LAB SEL-4211 (A-M)</u>	<u>Polarimetric Radar Data & Image Processing Center</u>
312/996-5140/- 5284/0195	<u>& Graduate Research Assistants Offices</u> <u>(1,550sq.ft)</u>

This spacious laboratory space (SEL-4211) with major experimentation laboratory in SEL-4211B and storage, basic tool and workbench in SEL-4211A houses the polarimetric radar data and image vector processing facilities with graduate research assistant stations totalling some 1,550 sq. ft. Also, the westward outdoor radar balcony (700 sq. ft.) will be operated from within SEL-4211G. An exit to the roof top Antenna Laboratory exists in SEL-4217/4220. The soundproof subroom SEL-4211G houses major vector graphics/image processing and printing equipment with a separate CL-owned cable link (duct) from the DEC-VAX 11/750 plus 780 Research Processing Computers in SEL-4210F, to the Polarization Radar Experimentation Laboratory in SEL-4211B, and to the Outdoor Radar Balconies.

<u>Room SEL-4211 A</u> (To be made available during FY 84)	Equipment Storage & Basic Tool Room with Work bench workshop Mr. Richard Foster, Laboratory Supervisor Custodian (to be appointed) (215 sq. ft.)
<u>Room SEL-4211 B</u> (To be made available during FY 84)	Polarization Radar Experimentation Laboratory with cable duct to Roof Top Antenna Range (245 sq. ft.) Mr. Robert B. Lemkowski, Radar Engineer Radar Technician (to be appointed)
<u>Rooms SEL-4211 C,D,E,F 996-5140</u>	Graduate Research Assistant Stations (two RA's per room with access to one VT-100 terminal per room)
<u>Room SEL-4211 H</u>	Electronic Equipment Storage Room
<u>Room SEL-4211 G</u> (312) 996-5284	Vector Graphics/Image Processors Computer Equipment Operator (to be appointed)
<u>Space SEL-4211 K:</u> (312) 996-5284	Research Library/Discussion Area/- Microfiche Reading Facility
<u>Space SEL-4211 L:</u>	Research Report Preparation Station Report Storage Facility
<u>Space SEL-4211 M:</u>	Special Computer/Vector Graphics/ Word Processing Stations
<u>Outdoor Balcony West</u>	Radar balcony for outdoor propagation studies (675 sq ft.)
<u>LAB: SEL-4209: OFFICE OF ADVANCED ENGINEERING STUDIES AT UIC</u>	
(to be completed during FY 84/85)	Audio-Visual Display/Recording Studio & Lecture Center

In this spacious lecture room (1,014 sq.ft.), a modern Stero/Video Studio & Lecture Center with lecture recording and display equipment will be established and maintained by a stereo-video equipment operating engineer with audio-visual recording/display experience. The use of this Audio-Visual Studio/Lecture Center will be shared with other Research Laboratories of the College of Engineering. The audio-visual studio/lecture equipment is connected via cable duct to our DEC-VAX 11/750-780 Research Processing Computer Systems with DEC-Net facility so that advanced computer graphics/image storage and processing facilities on/off campus can be tapped. This Audio-Visual STUDIO/LECTURE Center will become the main graduate research seminar/lecture auditorium for graduate research assistant education of the Communications Laboratory utilizing all relevant recently advanced computer-aided lecturing tools available on the market.

LAB: SEL-4202/4222/4207: EXPERIMENTATION HALLS (2,053 sq. ft.)

The spacious hallways neighboring SEL-4209/4210/4211 will be utilized as experimentation halls in the near future. For this purpose and to properly ensure the security of this area, the doorway to the main downward staircase in SEL-4204, the elevator adjacent to SEL-4217, the upward rooftop staircases adjacent to SEL-4217/4220 will receive security locking (identification card) systems. All doorways, hall connections, etc. to adjacent laboratories will be sealed as indicated on the Floor Plans UIC Bldg #607, Fourth Floor Plan (SW Corner).

SEL/607: ROOF-TOP ANTENNA & POLARIMETRIC RADAR RANGE (555 x 130 sq. ft.)

In the maintenance equipment (air conditioning/heating/fire protection, etc.) rooms (SEL-4220 and SEL-4217), are exits to the flat extensive (130 ft x 550 ft) roof-top of the Science & Engineering Laboratories Bldg. (607)/UIC. They are accessible and ideally located for antenna and polarimetric radar range experimentation in the 30GHz to 45 GHz region (K/G bands).

We are currently exploring the possibility of setting up such measurement ranges and we have requested cost estimates for construction of range pad, radar/antenna shed and target turn-table with remote control.

VI 3 OFF CAMPUS RADAR MEASUREMENT RANGES: The Glenview Naval Air Station

There is, at this time, no radar range available on the downtown campus of the University of Illinois at Chicago; and therefore, use of either the Naval Air Station at Glenview or of the University of Illinois Airport at Urbana is proposed. Until such outdoor high resolution polarization radar facilities are made available to us, we depend on measurement data produced elsewhere.

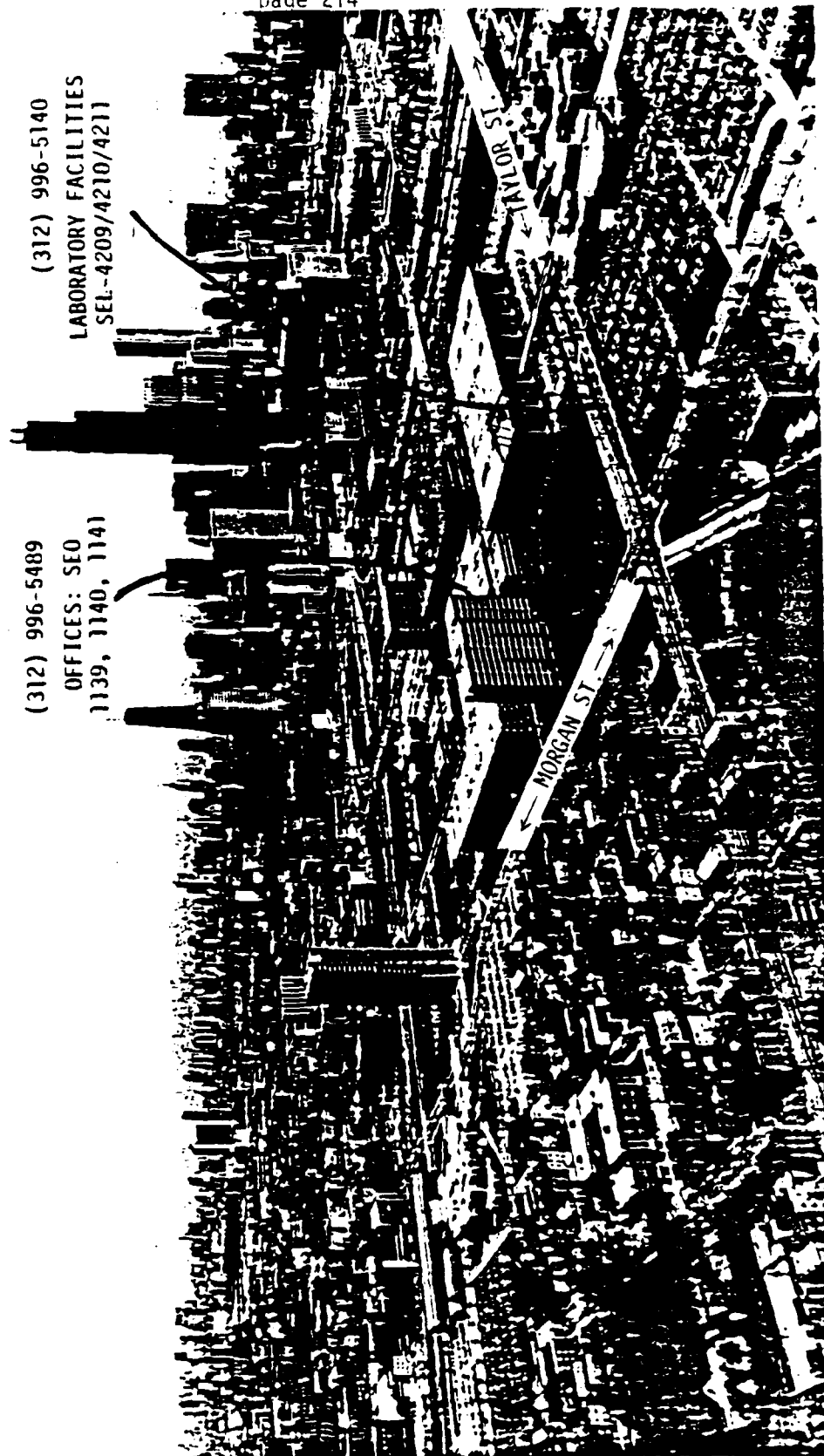
VI 4 Descriptive Material Appended to Chapter Six

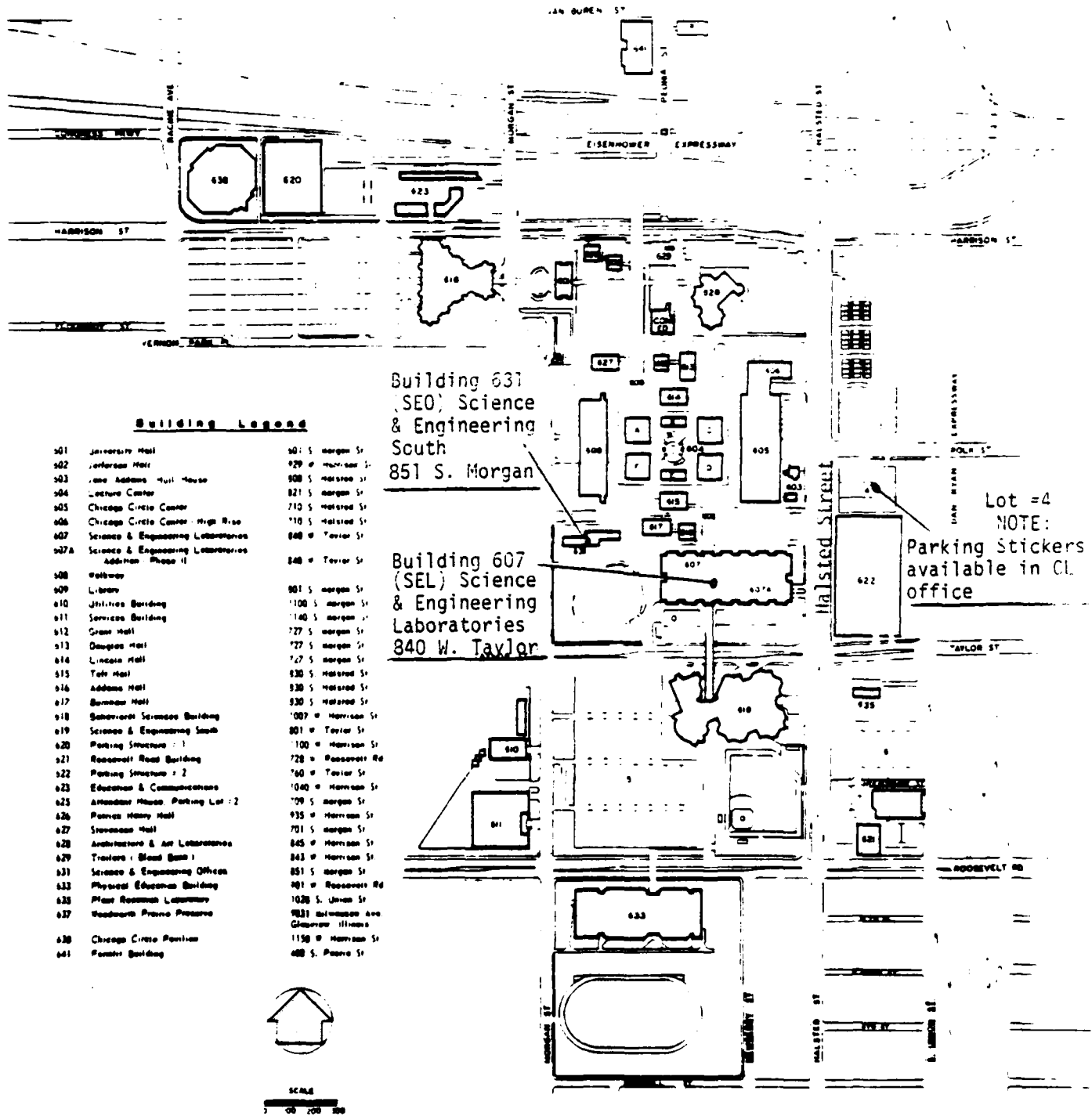
- A. Stereographic View of the UIC Campus with identification of the UIC-EECS-CL-EMID, Chicago Downtown Facilities
- B. UIC Campus Map
- C. SEL/607-BLDG-4TH Floor-Floor Plan (SW Corner)
- D. SEL/607-BLDG Roof Top-Floor Plan
- E. SEL/607-BLDG-4TH Floor SW/W-Wing Floor Plan (Labs: 4209, 4211; bldg. maintenance rooms 4217 & 4220, experimentation halls 4202, 4207 & 4222)
- F. GLENVIEW NAVAL AIR STATION/MAP

STEREOGRAPHIC VIEW OF THE UNIVERSITY OF ILLINOIS AT CHICAGO CAMPUS
WITH IDENTIFICATION OF THE EMID-CL-EECS-UIC FACILITIES

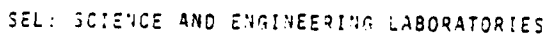
(312) 996-5140
LABORATORY FACILITIES
SEL-4209/4210/4211


(312) 996-5489
OFFICES: SEO
1139, 1140, 1141

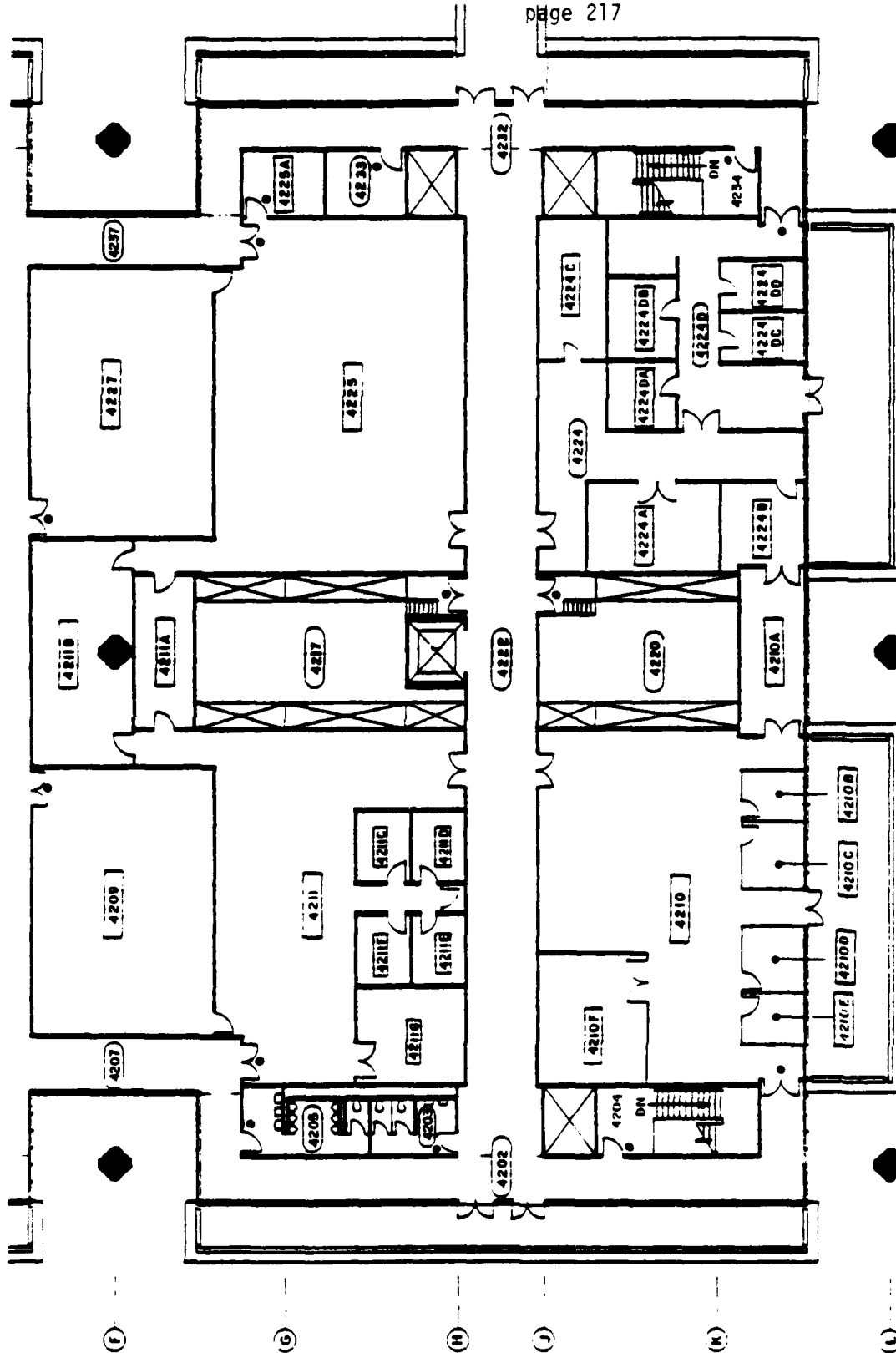




UNIVERSITY OF ILLINOIS CHICAGO CIRCLE CAMPUS



SCALE: 



UIC BLDG. #607 FOURTH FLOOR PLAN (S W CORNER)

SCALE: 0 5 10 15 20 30 40 50 60

CHAPTER VII

VII. DISTRIBUTION LIST

VII.1 Dedication Copy

Mrs. Mary Kennaugh (1)
4447 Lommisford, Lane East
Columbus, OH 43214

VII.2 Collaborating Research Institutes/Laboratories

IIT-Research Institute (1)
Electromagnetics Division
10 West 35th Street
Chicago, IL 60661
Attn: Dr. Ted Martin
Dr. Allen Taflove

ElectroScience Laboratory (1)
1320 Kinnear Road
Dept. of Electrical Engrg.
Ohio State University
Columbus, OH 43212
Attn: Dr. David L. Moffatt
Dr. Jonathan D. Young

Environmental Res. Inst. of Mich (1)
Radar Division
3300 Plymouth Road
P.O. Box 8618
Ann Arbor, MI 48107
Attn: Dr. Dimetrios T. Politis
Dr. Richard Larson

Applied Electromagnetics Lab (1)
UIUC, Dept. of Electr. Engrg.
Urbana, IL 61801
Attn: Dr. Georges A. Deschamps
Professor Emeritus
Dr. Yuen-Tze Lo

VII.3 US DoD Research Contract Offices/Laboratories

US Army

Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709
Attn: Mr. Richard Ulsh, Chief (20)
Publications Office
Dr. James W. Mink (1)
Electronics Division
Dr. Walter Flood (1)
Atmospheric Sciences Division

ERADCOM/DRDEL-CT-R (1)
2800 Powdermill Road
Adelphi, MD 20783
Attn: Mr. John Johnson

MICOM/DRSMI-REG (1)
Redstone Arsenal, AL 35809
Attn: Mr. Lloyd W. Root

DELCS-R-T (1)
Radar Division
Combat Surveillance
Ft. Monmouth, NJ 07703
Attn: Dr. William Fischbein

MERADCOM/DRDME-HS (1)
Ft. Belvoir, VA 22060
Attn: Dr. Karl Steinbach
Chief Scientist

US Navy

Office of Naval Research (1)
1030 East Green Street
Pasadena, CA 91106
Attn: Dr. Richard G. Brandt

Naval Weapons Center (1)
Code 381
China Lake, CA 93555
Attn: Dr. Guenter Winkler
Dr. Robert Dinger
Dr. David Reade

Office of Naval Research
Mathematics Division
800 N. Quincy Street
Arlington, VA 22217
Attn: Dr. Kenneth Davies (1)
Dr. David Lewis (1)
Dr. Charles Holland (1)
Dr. Hans Dolezalek (1)
Mr. Jim Hughes

Naval Surface Weapons Center
Code F-12
Dahlgren Laboratory
Dahlgren, VA 22448
Attn: Bruce Z. Hollmann (1)

Naval Air Systems Command (1)
Jefferson Plaza #1
6th Floor
Washington, DC 20361
Attn: Dr. Gerhard Heiche
Mr. Jim Willis

Naval Research Laboratory
Code 7946
Washington, DC 20375
Attn: Dr. Meril Skolnik (1)
Dr. Dennis Trizna
Mr. John Daley (1)

Naval Sea Systems Command (1)
Room 880, Crystal Plaza
Washington, DC 20362
Attn: Mr. Charles E. Jedrey

Naval Air Development Cntr (1)
Surveillance Radar
Warminster, PA 18974
Attn: Dr. Otto Kessler
Mr. Ray Dalton

Naval Electronics Systems Command (1)
Electronics Division
Code 6136
Washington, DC 20332
Attn: Dr. Robert DuPuy

U.S. Navy PMTC (1)
Code 1231
Point Mugu, CA 93042
Attn: Dean Menza

US Air Force

RADC-East (AFOSR-EMD) (1)
Electromagnetic Sciences Division
Hanscom AFB, MA 01731
Attn: Dr. Allan C. Schell

Wright Patterson AFB (1)
AFWAL/AARM-1
Wright Patterson AFB, OH 45433
Attn: Dr. Mehdi Shirazi

Rome Air Development Center (1)
OTSC
Griffiss AFB
Rome, NY 13441
Attn: Dr. Daniel Taurony
Dr. Vincent Vannicola
Dr. Keneth Stiefvater

Eglin Air Force Base (1)
AFATL-DLMT
Eglin AFB, FL 32542
Attn: Dr. Max McCurry

US Defense Advanced Research Project Agency

Tactical Technology (1)
1400 Wilson Boulevard
Arlington, VA 22209
Attn: Colonel Juergen Gobien

Lincoln - Laboratory (1)
P.O. Box 73
MA Inst. of Techn.
Lexington, MA 02173
Attn: Dr. Jerald Morse
Mr. Richard Barnes

VII.4 US National Polarimetric Radar Industry

Kent Space Center (1)
68th Ave. S., Mail Stop
06-09/Bldg 18-12
Kent, WA 98301
Attn: Mr. George Swetnam
Dr. Ray West

Westinghouse DEC (1)
Friendship International Airport
P.O. Box 746, Mailstop 1105
Baltimore, MD 21203
Attn: Mr. Norman Powell
Mr. Robert Raven

The Bendix Corporation (1)
43 Willaims Ave./MC 2/17A
Teterboro, NJ 07608
Attn: Dr. James Schuchardt

IIT Gilfillan (1)
Systems Analysis Group
7821 Orion Avenue
Van Nuys, CA 91409
Attn: Dr. D.E. Hammers

Martin-Marietta (1)
P.O. Box 3999
Seattle, WA 98124
Attn: Dr. Robert Green

General Dynamics (1)
Advanced Technology
P.O. Box 2507
Pomona, CA 91769
Attn: Dr. Hans-Peter Schmid

Radio Corporation of America (1)
Radar Systems Division
RCA Building 108-210
Moorestown, NJ 08057
Attn: Dr. Samuel M. Sherman

Scientific Atlanta
Radar Instrumentation Division
3845 Pleasantdale Road
Atlanta, GA 30340
Attn: Dr. Doren Hess

Honeywell SRC (1)
Aerospace & Defense Group
2600 Ridgway Parkway
P.O. Box 312
Minneapolis, MN 55440
Attn: Dr. Raja Suresh
Dr. James Marier Jr.

McDonnell Douglas (1)
Research Laboratory
Electromagnetics Division
P.O. Box 516
St. Louis, MS 63166
Attn: Dr. Louis Mitschang
Dr. Carl J. Leader

The Bendix Corporation (1)
400 Beiger Street
Mishiwaka, IN 46544
Attn: Dr. John Gannaway

General Electric (1)
Military Electronics Sys.
Adv. Development Engrg.
Syrause, NY 13221
Attn: Dr. Richard Taylor

Defense Systems, Inc. (1)
6804 Poplar Place
McLean, VA 22102
Attn: Dr. Henry Mullaney

General Dynamics (1)
Convair Division
5001 Kearney Villa Road
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